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CONTENTS

Geology of the Uranium Deposits in the Cochetopa Mining District, Saguache and Gunnison Counties, Colorado ..... *Roger C. Malan and Henry W. Ranspot* 1

Petrology and Preparation of Certain (Permian) Coal Seams of India ..... *C. E. Marshall* 20

Sulfide Solubility in Aqueous Solutions ..... *Gerald K. Czamanske* 57

The Nature of Davidite ..... *Alick W. G. Whittle* 64

Some Aspects of the Origin of the Ironwood Iron-Formation of Michigan and Wisconsin ..... *N. King Huber* 82

The Elk Ridge-White Canyon Channel System, San Juan County Utah: Its Effect on Uranium Distribution ..... *Henry S. Johnson, Jr., and William Thordarson* 119

Some Geochemical Considerations on Lead-Isotope Dating of Lead Deposits ... *R. W. Boyle* 130

Scientific Communications:

Occurrence of Jordanite At Balmat, New York ..... *John S. Brown* 136

Lead Isotopes from Balmat Area, New York ..... *John S. Brown and J. L. Kulp* 137

Discussions:

Temperatures and Depths of Formation of Sulphide Ore Deposits at Gilman, Colorado ..... *David J. McDougall* 140

Tungsten Mineralization in Hong Kong and the New Territories ..... *B. P. Ruxton* 142

Reviews:

Thirteen Reviews of Recent Russian Literature On Economic Geology .. *C. F. Davidson* 144

Bibliography and Index of Literature on Uranium and Thorium and Radioactive Occurrences in the United States. Parts 1–5. (Margaret Cooper) 146

Introduction to Historical Geology, 2nd Edit. (R. C. Moore) 147

Mineralogy and Geology of Radioactive Raw Materials (E. Wm. Heinrich) 147

Coastal and Submarine Morphology (Andre Guilcher) 148

Clays and Clay Minerals, Annual Conference Proceedings (Ed. by Ada Swineford) 149

Contributions in Geophysics in Honor of Beno Gutenberg (Ed. by H. Benioff, M. Ewing, B. F. Howell, Jr., and F. Press) 149

Books Received ..... *James M. Allen and John W. Salisbury* 149

Scientific Notes and News 158

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GEOLOGY OF THE URANIUM DEPOSITS IN THE COCHETOPA MINING DISTRICT, SAGUACHE AND GUNNISON COUNTIES, COLORADO

ROGER C. MALAN AND HENRY W. RANSPOT

CONTENTS

	PAGE
Abstract	1
Introduction	2
General geology	4
Geologic history	4
Stratigraphy	4
Structure	6
Uranium deposits	6
Summary of uranium mining and exploration in the area	6
Principal deposits	7
Los Ochos claims	7
Kathy Jo claims	15
La Rue claims	15
Other prospects	16
Equilibrium relationships	16
Conclusions	17
Origin of the ore deposits	17
Criteria relating to localization of uranium minerals in the Cochetopa mining district	18
References	19

ABSTRACT

Vein-type uranium deposits of geologic interest and commercial significance occur in the Cochetopa mining district, Saguache and Gunnison Counties, Colorado. The uranium minerals in these deposits have been precipitated from hypogene solutions probably related to Tertiary igneous activity in the district. Silicification and brecciation of the sedimentary rocks in the Morrison formation and the Dakota sandstone, in and adjacent to fault zones, controlled deposition of uranium minerals from hydro-

thermal solutions. The most important deposits in the district are at the Gunnison Mining Company's Los Ochos claims where substantial reserves of ore in pipelike and in vertically tabular bodies have been blocked out. Pitchblende, the dominant uranium mineral, is associated with abundant clay and minor amounts of marcasite. As a result of studies carried out in the district, certain pertinent geologic criteria on ore localizing influences have been established.

INTRODUCTION

THE Cochetopa mining district is located in northwestern Saguache and in southern Gunnison Counties in southwestern Colorado, about 20 miles southeast of Gunnison (Fig. 1).

The area of interest is approximately 10 miles long by 5 miles wide and is that part of the Cochetopa mining district in which significant uranium

FIG. 1. Geologic map and section of a portion of the Cochetopa mining district.

occurrences are known. North-flowing Cochetopa Creek divides the area into two nearly equal parts.

Except for steep, dissected canyon walls along Cochetopa Creek, the region is characterized by rolling terrain interrupted by small mesas and cliffs capped by resistant rocks. Two domes of volcanic material create prominent landscape features. At higher elevations, outcrops of volcanic flows locally form well-exposed rims and caps. Elsewhere, farther from dissecting streams, slopes of volcanic erosional remnants are blanketed by stabilized detritus. Average elevation of the Cochetopa area is 9,000 feet above sea level; maximum relief is approximately 1,000 feet.

Dissection along Cochetopa Creek and, to a lesser extent, along its tributaries has provided good exposures of the more resistant formations. Precambrian rocks are the best exposed in the district with nearly continuous outcrops along the canyon walls bounding Cochetopa Creek. Of the sedimentary rocks, the Dakota sandstone and, to a lesser extent, the Salt Wash sandstone member of the Morrison formation form discontinuous rim exposures. Mudstones and shales of the Brushy Basin shale member of the Morrison formation and the Mancos shale are poorly exposed. Erosional remnants in the vicinity of mineralized bodies owe their resistance to silicification.

The original discovery of uranium in the Cochetopa district was made in the summer of 1954, at what is now the Gunnison Mining Company's Thornburg mine on the Los Ochos claims. Substantial reserves have been developed at this property, and most of the ore shipped from the district has originated here. A number of other properties are being explored. The area has been intensively prospected and several thousand lode claims have been staked.

Mining in the district has been predominantly underground by exploratory drifting, winzing, and raising. One small open-pit operation has been intermittently active in the southern part of the district.

Field work for this report was done during various periods from the time of the first discovery in the district through March 1956. Detailed studies, including surface and underground geologic mapping, were carried out on selected properties in order to establish pertinent geologic criteria for ore localization in the district. The study was made as part of the program of the Denver Area Office, Raw Materials Division, U. S. Atomic Energy Commission.

The writers wish to thank Messrs. Vance and Garth Thornburg, Gunnison Mining Company, for the courtesies extended during the examination of properties under their control. Permission from Mr. E. V. Storey, Monarch Mining and Development, Inc., to examine and map their properties is also appreciated. The cooperation of other property owners aided greatly in carrying out this project.

Laboratory analyses, including radiometric and chemical assaying, mineralogic, petrographic and spectrographic studies were completed in the laboratories of the United States Geological Survey at Denver, Colorado.

The results of preliminary work at the Los Ochos claims were reported by Derzay (2).

GENERAL GEOLOGY

Geologic History

The Precambrian complex, comprising gneisses and schists intruded by granite and pegmatite, was beveled by erosion during pre-Morrison times. Subsequently, the Morrison formation of Upper Jurassic age and the Dakota sandstone and Mancos shale, both of Upper Cretaceous age, were deposited over this Precambrian surface. During Tertiary time, a series of volcanic flows blanketed the district. Because of the district's peripheral location relative to the center of the San Juan volcanic-flow province, the accumulation of volcanics, with local exceptions, was not great. In the late Miocene, a domal uplift to the southwest slightly tilted the formations of the district, imposing upon them a northeasterly regional dip. Prevolcanic and post-volcanic faulting was the major control in localizing uranium minerals.

Stratigraphy

Rock units range from Precambrian through Tertiary in age (Fig. 2). In the northern part of the district, the Precambrian metamorphic complex consists of quartz-biotite schist, hornblende gneiss and minor ultrabasic rocks; in the southern part of the district, the basement rocks were intruded by later Precambian coarse-grained, pink, biotite granite and granite gneiss. Pegmatite stringers and dikes cut the granitic rocks. In the vicinity of the Thornburg mine, the contact between granite and schist is gradational; there are unassimilated schist remnants in the granite and lit-par-lit intrusions in the schist.

The Morrison formation is approximately 300 feet thick and lies directly on the Precambrian erosional surface. The lower 40 feet is a fine-grained, buff to cream-colored, crossbedded sandstone with some siltstone and mudstone tentatively correlated with the Salt Wash sandstone member. The upper 256 feet, the Brushy Basin shale member, is an alternating series of variegated mudstones, siltstones, and shales containing lenticular sandstone beds. Microscopically, the mudstone has been identified as largely quartz and clay minerals with some microcline and very minor amounts of tourmaline.

The Dakota sandstone lies unconformably on the Morrison formation. It is predominantly a moderately well-cemented, crossbedded, buff to cream colored, fine-grained sandstone with a maximum thickness of 105 feet; in part, it is arkosic. The basal unit of the formation consists of a continuous silicified pebble conglomerate 5 to 10 feet in thickness. Three shale beds are present in the upper part of the formation. Differential erosion of this upper member has produced a series of offset benches.

The Mancos shale, conformably overlying the Dakota sandstone, is the youngest sedimentary unit in the district and is approximately 150 feet thick in the area mapped. It is a gray to black sandy shale with a white thin-bedded basal sandstone about 10 feet thick. East of Razor Creek, in the eastern part of the district, the formation attains a thickness of approximately 300 feet.

Volcanic erosional remnants of the Miocene Potosi volcanic series overlie the sedimentary rocks. The Conejos andesite, composed of andesitic and tuffaceous rocks, is the oldest known unit of this series in the district. The Alboroto quartz latite flow overlies the Conejos and is composed of biotite-augite-quartz latite and rhyolitic tuffs. The Piedra rhyolite flow overlies the

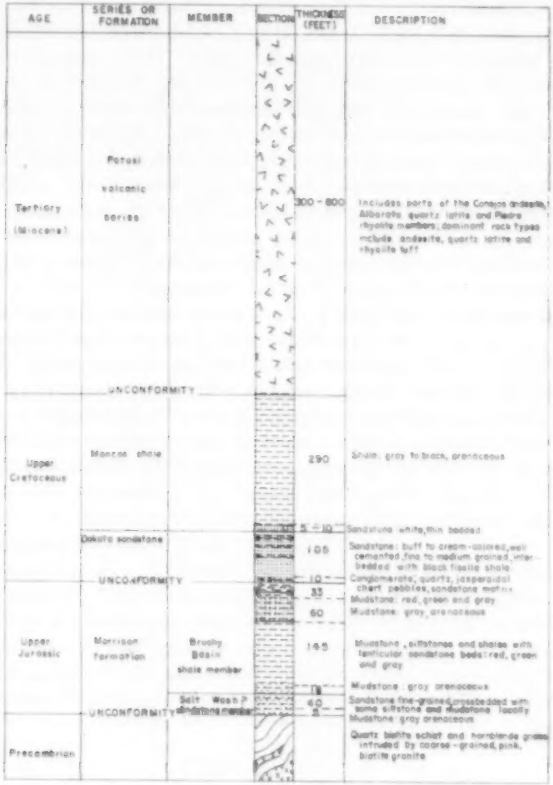

FIGURE 2. GENERALIZED COLUMNAR SECTION OF THE COCHETOPA DISTRICT

Alboroto and is essentially a rhyolitic tuff. Contacts between members of the Potosi volcanic series were not established. The series totals at least 800 feet in thickness in local erosional remnants. The preceding correlations, using the classification of Cross and Larsen (1) were made on the basis of only a few field examinations.

The youngest rocks in the district occur in a cluster of late Miocene intrusives approximately 3.5 miles southeast of the Thornburg mine. They are of intermediate composition and postdate the volcanic rocks.

Structure

Faults and shears that cut Precambrian, Mesozoic and Tertiary rocks were important in controlling the movement of uranium-bearing hydrothermal solutions and the subsequent localization of uranium minerals.

Fault trends in the district are variously oriented (Fig. 1). Based on photogeologic interpretations and observations made in the vicinity of numerous prospects, there is a suggestion that east and northeast-trending faults and shear zones are more persistent and abundant. It is believed that most of the faults with the greatest continuity and causing the greatest displacement, both in and near the district, displace Cretaceous formations but have not affected rocks younger than Cretaceous in age (3). However, in the southern part of the Cochetopa district, the entire rock section has been downdropped by three subparallel step faults so that volcanic flows to the south are at the same elevation as Precambrian rocks to the north of the faults. Along the inferred trace of a fault which is on the projection of one of these step faults, the Dakota sandstone is intensely silicified and at one point contains an ore-grade concentration of secondary uranium minerals.

The most important east-trending fault in the district, the near-vertical Los Ochos fault, is traceable for 3½ miles. It is younger than the Mancos shale but cannot be dated with reference to the Tertiary volcanic rocks as they have been removed, by erosion, along its trace. The fault contains gouge from 1 to 3 feet in thickness and has vertically displaced formational contacts about 140 feet at the Thornburg mine. One mile east of the mine, the displacement is 120 feet and 1½ miles farther east, no vertical displacement is evident. At the Los Ochos claims, the fault splits into two subparallel components for a distance of 800 feet after which the two branches converge into a single fault. One of the ore bodies at the Thornburg mine is located within this split. There are southwest-trending faults that join the Los Ochos fault east of the Thornburg mine. These faults are prominent southward from the Los Ochos fault, but none are known that join on the north side of the fault.

Fault structures, obscured by soil and overburden, are determined with difficulty on the ground. Because fault traces may be recognized more easily on aerial photographs, photogeologic interpretation has had useful application in the district.

URANIUM DEPOSITS

Summary of Uranium Mining and Exploration in the Area

The initial discovery of uranium in the district was at the Los Ochos claims where abnormal radioactivity and visible uranium minerals were noted at outcrops. Core drilling by the Gunnison Mining Company, lessees of the claims, provided data that indicated potentially commercial ore bodies at depth. An inclined shaft, driven toward ore located by this core drilling, was commenced in October 1954. Ore was intersected in late December of that year. Exploration and development work is still in progress and has resulted in the blocking out of substantial ore reserves in five ore bodies along the Los Ochos fault.

Exploration at the Gunnison Mining Company's East mine (Fig. 1) on the Kathy Jo claims has revealed only one small ore body adjacent to the Los Ochos fault. There are no other underground uranium mining operations in the district.

Ore mined from an open cut has been stockpiled at the La Rue claims in the southern part of the district. Other exploration in the district has been largely negative.

Principal Deposits

Los Ochos Claims.—The Gunnison Mining Company's Thornburg mine is located on the Los Ochos claims in the north-central portion of the district in sec. 4, T. 47 N., R. 2 E., N.M.P.M. Sedimentary rocks along the Los Ochos fault are silicified and brecciated. Abnormal radioactivity is intermittently present along the fault trace and visible secondary uranium minerals locally constitute commercial ore.

During the period of field investigations, development on ore bodies Nos. 1 and 2 was essentially completed. Since that time, however, three additional smaller ore bodies have been discovered. Detailed descriptions are given of the more significant Nos. 1 and 2 ore bodies.

Ore body No. 1 appears to have been controlled by a physically favorable environment at the east juncture of the previously described split of the east-trending Los Ochos fault (Fig. 3). Projection of the exposures in the incline indicates that the nearly flat-lying Precambrian-Morrison contact dropped 65 feet on the north side of the south segment of the Los Ochos fault, 70 feet westward from the juncture. In this vicinity, results of underground drilling indicate that this same contact dropped an additional 83 feet on the north side of the north segment of the fault.

The sequence of events relating to deposition of the ore appears to have been as follows: 1) initial displacement on the Los Ochos fault; 2) invasion of the fault and wall rocks by solutions resulting in intense silicification of the sedimentary rocks along the fault; 3) renewed movement along the fault in which a linear zone of silicified rocks adjacent to the fault were extensively brecciated and fractured; 4) introduction of marcasite and pitchblende.

Along the main haulage level, Morrison mudstone forms the north side of the north segment of the Los Ochos fault and Precambrian granite and schist lie on the south side of the south segment. A wedge of silicified and brecciated Morrison sandstone lies between the two segments. In this wedge, the contact between Precambrian schist and Salt Wash sandstone is near the floor of the main haulage level.

Raking approximately 80° E, ore body No. 1 is a pipelike ore shoot roughly triangular in plan. Brecciation of the sandstone and shearing of the schist created a favorable physical environment for channeling uranium-bearing hydrothermal solutions. A mineralized exposure indicates continuity of this ore body to the surface though on a reduced cross section. Drilling results indicate that ore extends below the haulage level.

Ore body No. 2 is situated 380 feet west of ore body No. 1. A fractured and brecciated zone of Morrison sandstone and mudstone lies north of and

adjacent to the north segment of the Los Ochos fault. This brecciated zone is believed to have been developed during the second stage of movement on the Los Ochos fault.

Although ore body No. 2 is limited on the south by the north segment of the Los Ochos fault, the control of its emplacement is inconclusive elsewhere. As illustrated in section B-B′ (Fig. 3), the dip of the fault changes from nearly vertical at the main level to approximately 60° N at the bottom of the winze, 50 feet below.[1] In this locality, on the north side of the fault, the sedimentary rocks have been silicified from the Precambrian contact to the surface, but on the south side, only the Salt Wash sandstone and the lowermost Brushy Basin member appear to have been silicified. This suggests that, during the initial phase of hydrothermal activity, the greatest volume of silica-bearing solutions passed through a zone on the north side of the fault. During the second stage of differential movement, silicified rock, above the flattening of dip and on the north side of the fault, was extensively fractured and brecciated. This provided a favorable environment for the emplacement of concentrations of uranium minerals from hydrothermal solutions migrating upward along the fault.

At and near the outcrop of ore body No. 1, the secondary uranium minerals autunite and uranophane fill interstices of silicified and brecciated mudstones of the Brushy Basin shale member of the Morrison formation. Underground, silicified and brecciated sandstone and mudstone and altered metamorphic rocks contain black, sooty to semi-hard, fine-grained pitchblende of hypogene origin in veinlets filled with marcasite and clay minerals, and as finely disseminated grains in fractures and quartz gangue. The pitchblende in places forms a coating on grains of marcasite. A minor amount of an unidentified orange-yellow uranium mineral is present in a wedge of pegmatite intruded into schist. Uranopilite [$(UO_2)_6(SO_4)(OH)_{10}\cdot 12\,H_2O$] and sparse amounts of zippeite [$(UO_2)_2(SO_4)(OH)_2\cdot 4\,H_2O$] form as a deep yellow encrustation on the heavily mineralized schist portion of ore body No. 1 after a few weeks exposure. About 18 months later, a green-colored hydrous uranium mineral, johannite [$Cu(UO_2)_2(SO_4)_2(OH)_2\cdot 6\,H_2O$], formed on the walls in this same area.

Chalcedony, barite, clay minerals and quartz blebs comprise the gangue minerals. Chalcedony occupies veinlets in brecciated sedimentary rocks. Barite, present as yellowish tabular crystals, appears to be older than pitchblende. Quartz blebs, pods, and veinlets vary from light to dark. Two generations of marcasite, I and II, occur as fine disseminations, veinlets and small concretionary and reniform structures.

Based largely on petrographic studies of numerous specimens of mineralized Salt Wash sandstone from the Thornburg mine, the following sequence of events from oldest to youngest is indicated: 1) silicification; 2) fracturing

[1] As revealed by recent exploration in upper levels, the dip of the fault changes from nearly vertical to approximately 65° N, 150 feet above the main level. In section B-B′ (Fig. 3), it is evident that the north and south segments of the fault would join if projected above the present erosional surface. These segments may also join at a depth greater than exploration has proceeded below the main haulage level. Thus, a cymoidal fault pattern with closure in section as well as in plan is probable.

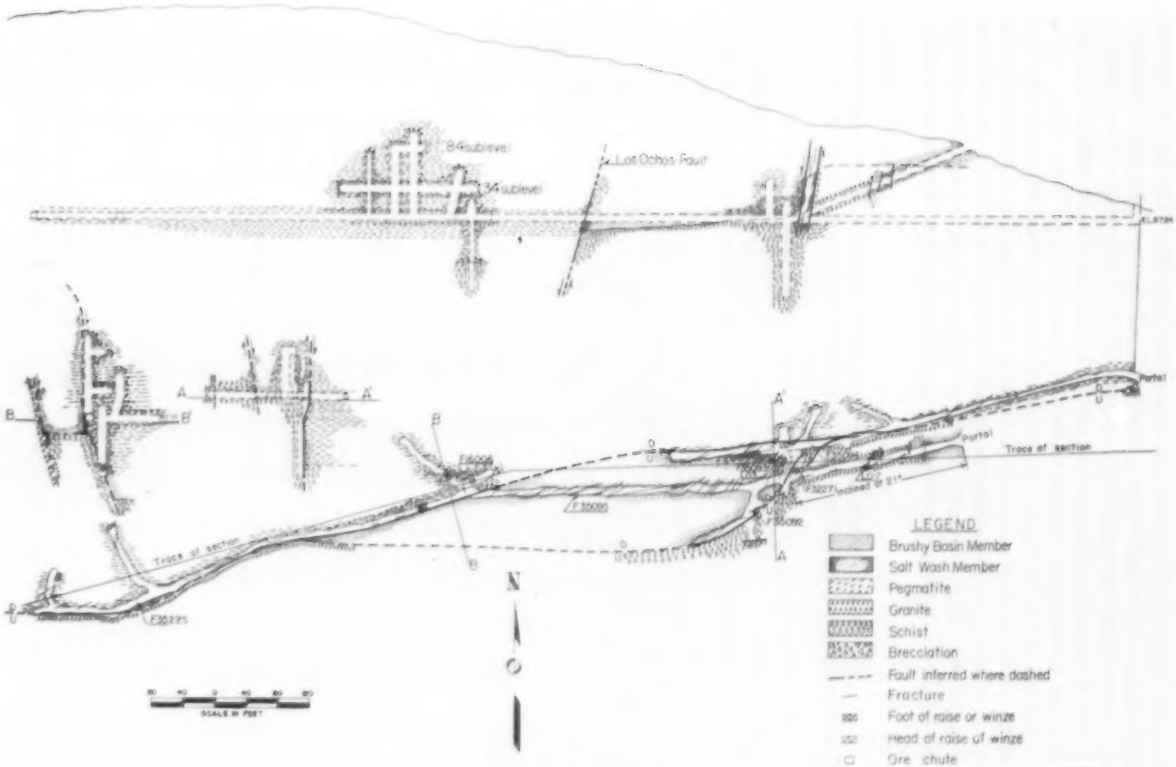

FIG. 3. Geologic plan and sections of the Thornburg mine.

and brecciation; 3) introduction of marcasite I and clay minerals; 4) renewed fracturing; 5) introduction of marcasite II; 6) introduction of pitchblende; and 7) introduction of kaolinite as fracture fillings. Marcasite II coats marcasite I as radial aggregates within the clay areas of the veinlets and is also present as disseminated specks in the host rock.

Rock alteration was intense in the vicinity of the ore bodies and has affected a zone along the Los Ochos fault for more than one-fourth mile. Kaolinization, chloritization and sericitization of the basement rocks and silicification of the Salt Wash sandstone and Brushy Basin shale members of the Morrison formation form an envelope of argillic and silicic alteration minerals

TABLE 1

SPECTROGRAPHIC ANALYSIS OF SAMPLES FROM THE THORNBURG MINE AND

Element	Schist						
	Mineralized				Weakly mineralized	Unmineralized	
	Altered					Unaltered	
	Lot 2	Lot 7	F–32271	F–35094	LO–7	F–35224	F–35223
Si	XX.	XX.	XX.	XX.	XX.	XX.	XX.
Al	XX.	XX.	XX.	XX.	XX.	XX.	XX.
Fe	X.–	X.	X.	.X+	X.+	.X+	X.+
Ca	.X–	.X–	.X–	.0X+	.X–	.X+	X.–
Mg	.X–	.X	.0X+	.X–	X.–	X.–	X.–
Na	.X	.X–	.X–	.X–	.X–	X.	X.+
K	X.	X.	X.–	X.	X.	X.+	X.+
Ti	.X	X.–	.X	.X+	.X	.X+	.X+
P	0	.X	0	0	0	0	0
Ba	.0X+	.0X+	.X–	.0X+	.0X–	.X–	.X–
Mn	.0X–	.00X	.00X	.00X	.X–	.0X–	.X–
Sn	.0X	.X	.0X	.0X	.0X+	.0X–	.0X
Ag	Tr.	.000X–	0	.000X	0	0	0
As	0	.X–	0	0	0	0	0
B	.00X–	.00X–	0	.00X	0	0	0
Be	.000X–	.000X–	0	.000X	0	Tr.	.000X–
Cb	.0X–	.0X–	.0X–	0	0	0	0
Ce	0	.0X+	.0X	.0X–	0	0	0
Co	.00X	.0X–	.00X	.0X–	.000X+	.00X–	.00X–
Cr	.00X	.00X	.000X+	.00X–	.00X–	.00X	.00X
Cu	.0X	.0X–	.0X	.00X	.00X	.00X	.00X+
Ga	.00X	.00X	.00X–	.00X–	.00X–	.00X	.00X
Ge	0	0	0	0	0	0	0
La	.00X	.0X	.00X+	.00X	.00X	.00X	.00X+
Mo	.0X–	.0X–	.0X–	.0X+	0	0	0
Nb	.00X	.0X–	.00X–	.00X	.00X–	.00X–	.00X–
Na	0	.0X	Tr.	.00X	.0X–	0	Tr.
Ni	.00X	.0X–	.00X	.0X	.000X+	.00X	.00X–
Pb	.0X+	.0X+	.00X	.0X+	Tr.	.00X–	.00X–
Sb	0	0	0	0	0	0	0
Sc	.000X	.00X–	Tr.	.00X–	.00X	.00X	.00X
Sn	.00X–	.00X–	0	0	0	0	0
Ti	.00X	.0X–	0	0	0	0	0
U	.X+	.X+	X.–	.X	0	0	0
V	.00X+	.00X+	.00X–	.00X	.00X+	.0X–	.0X–
Y	.00X	.0X–	.00X	.00X	.00X	.00X+	.00X+
Yb	.000X+	.00X–	.000X	.000X	.000X	.000X+	.000X+
Zn	.0X	.0X	0	0	0	0	0
Zr	.0X	.0X	.0X	.0X	.0X+	.0X	.0X

Looked for but not detected: P, Au, Bi, Dy, Er, Gd, Hf, Hg, In, Ir, Os, Pb, Pt, Re, Rh, Ru, Sm, Ta, Th, Te, and W.

Analyses by P. J. Dunton and N. M. Conklin of the U. S. Geological Survey, Denver Laboratory.

around the ore bodies. Zonal relations of hydrothermal alteration products were not established because of limited petrographic data. The clay minerals kaolinite, montmorillonite and illite were identified by X-ray diffraction methods. These clays are abundant in the ore bodies; they occur as a matrix in brecciated silicified sandstone and mudstone and in marcasite and pitchblende-bearing veinlets that cut the sedimentary rocks. Chlorite and a lesser amount of sericite are present in samples of mineralized schist. In zones of more intense alteration, feldspars in the crystalline rocks are generally reduced to a groundmass of clays. Alteration of the hematite pigment has resulted in bleaching the red and green variegated mudstones of the Brushy Basin to

TABLE 1.—*Continued*

FROM UNMINERALIZED LOCALITIES IN THE COCHETOPA MINING DISTRICT

Element	Sandstone						
	Mineralized		Weakly mineralized			Unmineralized	
	Silicified					Unsilicified	
	F–35093	F–35225	LO–3	F–35092	F–35095	F–35220	F–35219
Si	XX.	XX.	XX.	XX.	XX.	XX.	XX.
Al	XX.	X.	X.–	X.	X.	.X+	.X+
Fe	.X	X.+	.X	X.+	.X	.0X+	.X–
Ca	.0X	.0X	.0X+	.X–	.0X	.0X+	.0X
Mg	.0X+	.X–	.0X	.0X+	.X	.0X	.0X
Na	.0X	.0X+	.0X	.0X	.0X	Tr.	Tr.
K	X.–	.X+	0	0	0	0	0
Ti	.0X	.0X+	.0X	0	0	.0X	.0X
P	0	0	0	0	0	0	0
Ba	.00X+	.0X+	.0X–	.0X	.X–	.00X–	.0X–
Mn	.00X	.00X	.00X	.0X–	.00X	.000X+	.000X+
Sn	.0X–	.0X	.00X	.0X–	.0X–	.00X	.00X
Ag	.000X	.000X–	0	0	0	0	0
As	0	.X+	0	0	0	0	0
B	.00X–	.00X	.00X–	.00X	.00X	Tr.	0
Be	.000X–	Tr.	0	0	0	0	0
Cb	0	0	0	0	0	0	0
Ce	0	0	0	0	0	0	0
Co	.00X+	.00X+	.000X+	.00X	.00X	0	0
Cr	.00X–	.000X+	.00X–	.00X–	.000X+	.000X–	.000X
Cu	.0X	.0X	.00X+	.0X–	.00X	.000X–	.000X–
Ga	.00X–	Tr.	0	0	0	0	0
Ge	0	.00X	0	0	0	0	0
La	0	0	0	0	0	0	0
Mo	.X–	.00X	.000X	.0X–	.00X	0	0
Nb	.00X–	.00X–	.00X–	.00X–	.00X–	0	0
Na	0	0	0	0	0	0	0
Ni	.00X	.00X+	.000X+	.00X	.00X	0	0
Pb	.X+	.0X	.0X–	.0X	.00X–	0	0
Sb	.0X	0	0	0	0	0	0
Sc	.000X	.000X+	0	0	0	0	0
Sn	0	0	0	0	0	0	0
Ti	0	Tr.	0	0	0	0	0
U	.X+	.0X	0	0	0	0	0
V	.00X	.00X	.00X	.00X	.00X	0	0
Y	.00X	Tr.	.00X–	.00X–	0	0	0
Yb	.000X	Tr.	.000X–	.000X–	0	0	0
Zn	.X	0	0	.X	.0X+	0	0
Zr	.0X	.00X+	.00X+	.0X–	.0X–	.00X+	.00X+

Example of notation used:

Subgroups	Size of subgroup
.X+	From about 0.5% to about 1.0%
.X	From about 0.2% to about 0.5%
.X–	From about 0.1% to about 0.2%
XX.	From about 10% to 100%

Table 1 Continued on page 12

TABLE 1.—*Continued*

Element	Mudstone			
	Mineralized		Unmineralized	
	Silicified		Unsilicified	
	F-16005	F-16006	F-35222	F-35221
Si	XX.	XX.	XX.	XX.
Al	X.+	X.	XX.	XX.
Fe	X.+	X.	X.	X.−
Ca	.0X+	.0X	.X−	.X
Mg	.0X+	.X	.X+	X.−
Na	0	.X−	.X−	.X−
K	0	X.−	X.	X.
Ti	.0X+	.X−	X.	.X
P	0	0	0	0
Ba	.0X	.0X−	.0X+	.0X+
Mn	.0X	.0X	.0X+	.0X+
Sn	.0X+	.0X+	.0X	.0X−
Ag	Tr.	.000X−	0	0
As	0	0	0	0
B	0	.00X	.0X−	.00X+
Be	Tr.	.000X	.000X	.000X−
Cb	0	0	0	0
Ce	.0X−	0	0	0
Co	.0X−	.00X+	.000X+	.000X+
Cr	.00X	.00X	.00X	.00X−
Cu	.0X	.0X	.00X−	.00X−
Ga	.000X+	.00X	.00X−	.00X−
Ge	.00X	.00X	0	0
La	.00X+	.00X	.00X	.00X
Mo	.00X	.0X	0	0
Nb	Tr.	.00X−	.00X−	.00X−
Na	.0X−	Tr.	0	0
Ni	.0X−	.0X−	.00X−	.000X+
Pb	.0X	.X	.00X−	.00X−
Sb	0	.0X−	0	0
Sc	.000X+	.000X+	.00X−	.00X−
Sn	.00X−	Tr.	0	0
Ti	0	0	0	0
U	.X	.X−	0	0
V	.00X+	.00X+	.00X	.00X
Y	.00X	.00X−	.00X	.00X
Yb	.000X	.000X−	.000X+	.000X+
Zn	.0X−	.X−	0	0
Zr	.0X−	.0X−	.0X	.0X

gray or grayish green colors where that member has been silicified. In samples of silicified sandstone, quartz grains show secondary growth and sutured contacts. Minor amounts of tourmaline and microcline were identified in samples of sandstone and mudstone.

Spectrographic analyses were made of 12 mineralized samples of sandstone, mudstone and schist from the Thornburg mine. Similar analyses were made of six unmineralized equivalents of these rocks collected from nearby localities (Table 1). The locations from which samples in these two groups were collected are shown on Figures 1 and 3. The samples designated Lot 2 and Lot 7 are representative splits from two carload shipments that originated from ore body No. 1 at the Thornburg mine. The locations of these samples are not shown on the plan map of the mine as the ore was mined from various parts of this ore body. Samples F-35223 and F-35221 were collected outside the mapped area in localities 2.4 miles north and 2 miles northeast of the Thornburg mine. Abundance and deficiency ratios were determined for various elements by comparing their mean values in mineral-

ized and unmineralized rocks (Table 2). In the calculations, all samples in which uranium was spectrographically determinable, i.e., greater than 0.05 percent U_3O_8, were considered mineralized. In a number of samples, several elements are present in quantities below the limits of sensitivity. In cases

TABLE 2

ELEMENTAL ABUNDANCE AND DEFICIENCY RATIOS AT THE THORNBURG MINE (ORE/COUNTRY ROCK)

Sandstone			Mudstone				Schist			
Abundance ratio		Deficiency ratio	Abundance ratio		Deficiency ratio		Abundance ratio		Deficiency ratio	
Pb*	785.0	None	Pb	128.0			Pb	38.0		
Cu	230.0		Cu	23.0			Cu	2.0		
Mo*	154.0		Mo*	39.0			Mo*	60.0		
Co*	30.0		Co	15.0			Co	25.0		
Ni*	22.0		Ni	13.0			Ni	5.7		
Fe	18.0		Fe	2.2					Fe	1.8
Sr	14.0		Sr	3.0			Sr	2.3		
Al**	>8.0				Al**	>2.0				
Ge*	7.5		Ge*	14.0						
V*	7.0		V	2.1					V	3.0
Ba	5.0				Ba	3.0				
Ag*	5.0		Ag*	2.5			Ag*	3.0		
Mn	4.7									
Cr	4.5									
Y*	4.0									
Mg	3.2				Mg	5.3			Mg	2.0
Yb*	3.2				Yb	3.0				
La*	3.0		La	3.1			La	2.3		
Ga*	2.5		Ga	2.8						
Be*	2.0									
Zr	1.5				Zr	2.3				
			Sn*	2.5			Sn*	2.0		
							Cd*	19.0		
							Nb	3.9		
					Sc	2.0			Sc	1.8
					Ca	4.5			Ca	8.6
									Na	6.9
									K	2.5
					Ti	3.2				
					B	3.8				

The elements listed below also have probably been added to or subtracted from mineralized rocks. The absolute increase or decrease is not determinable because of poor standard sensitivity.

U		U		U	
Ce		K		Nd	
		Na		Zn	
		Zn			

* Determinations made in which an element was undetectable in some of the samples. Half the standard sensitivity value was arbitrarily used if the resulting value was not greater than 0.0025 percent.

** Determinations made in which an element is present in such abundance that its probable value covers a wide range within a subgroup. The ratio arrived at is the most conservative that is possible.

where the standard sensitivity is 0.005 percent or lower, an arbitrary value of one-half the standard sensitivity was assigned to the element. In unmineralized Salt Wash sandstone, these values appear to be conservative in their effect on abundance ratios when compared with the estimated geometric mean values of elements in unmineralized Salt Wash sandstone from the Colorado Plateau (5). Spectrographically undetected elements having standard sensitivity values greater than 0.005 percent U_3O_8 were not utilized in calculating these ratios.

Lead, molybdenum, cobalt and, to a lesser extent, nickel appear to be dominant extrinsic elements regardless of the host rock. Cadmium appears as an addition in schist only. Additions of copper, sufficient to suggest a probable origin from ore-bearing solutions, are present in the sandstone and mudstone but not in the schist. Iron and strontium are relatively abundant in mineralized sandstone as opposed to schist and mudstone. Germanium appears to be an extrinsic element in sandstone and mudstone but not in schist. Abundance ratios are generally appreciably higher in sandstone than in the other host rocks.

In mineralized zones, certain elements, believed to be largely intrinsic, appear to have been subtracted from the more chemically and mineralogically complex schist and mudstone and subsequently added to sandstone, which reveals no elemental deficiencies. This apparent redistribution of elements may have resulted from the action of mineralizing solutions of hydrothermal origin rather than by diagenesis. The ytterbium, aluminum, zirconium and barium in mineralized sandstone may have been derived, in part, from mudstone which, in mineralized zones, reveals a deficiency of these elements. Some of the vanadium and iron in sandstone and mudstone may have resulted from the impoverishment of these elements in mineralized schist. Some of the magnesium present in sandstone may have originated from mineralized mudstone and schist that have undergone a low-order impoverishment of that element.

The higher abundance ratios of metallic elements in mineralized sandstone as opposed to mineralized schist or mudstone are explained, in part, by the effect on the ratio of the variable intrinsic amounts of these elements in unmineralized equivalents of these host rocks. There is, however, an apparent variable environmental favorability affecting the precipitation of several accessory metallic elements.

There are variations in the elemental composition of uranium ore in the Salt Wash sandstone at the Thornburg mine as opposed to the mean concentration of elements in ores in that member on the Colorado Plateau (5). The abundance ratios of molybdenum, lead and copper are many times greater than the ratios determined for these elements in the Salt Wash ores of the Plateau. Cobalt and nickel occur in the same range of abundance, but vanadium and arsenic are relatively deficient in the uranium ore in the Salt Wash sandstone at the Thornburg mine as compared with the ores in that member on the Colorado Plateau. These variations suggest that mineralizing solutions were of a different chemical composition.

It should be emphasized that the preceding comparisons and conclusions

are statistically inconclusive because of the limited number of samples analyzed. Because of this restriction, correlation coefficients between uranium and accessory metallic elements were not established. The data, however, suggest that correlations between extrinsic elements in one host rock probably are not duplicated in the other host rocks.

Kathy Jo Claims.—The Kathy Jo claims, in sec. 3, T. 47 N., R. 2 E., N.M.P.M., lie immediately east of the Los Ochos claims and are held under a mining lease by the Gunnison Mining Company. The eastward projection of the Los Ochos fault is exposed in underground workings of the East mine where Precambrian biotite schist cut by granite and pegmatite stringers is in fault contact with mudstone and a sandstone lens. The relative movement along the fault is the same here as at the Los Ochos claims in that the north side has been dropped down. An irregular ore body in silicified and brecciated Morrison sandstone and mudstone is exposed in underground workings along the north side of the Los Ochos fault. This mineralized body is limited on the west by a small northeast-trending branch from the main fault. Seven of thirteen diamond drill holes, collared at the surface and penetrating the Los Ochos fault, intersected mineralized, silicified and brecciated mudstones and sandstones north of the fault. One of these holes penetrated the ore body explored by underground workings.

On these claims, a southwest-trending fault adjoins the Los Ochos fault on the south side at a point 800 feet east of the East mine. The area between the junctioning faults is underlain by a thin layer of Morrison sandstone overlying Precambrian rocks. Core from a drill hole penetrating this fault juncture was not mineralized.

Minor amounts of autunite and uranophane are present at the surface in silicified and brecciated Brushy Basin mudstone along the Los Ochos fault. Pitchblende, clays, and marcasite occur in silicified and brecciated sandstone exposed in the underground workings. Megascopic examination indicates that this mineralized body is paragenetically similar to the ore bodies at the Los Ochos claims.

La Rue Claims.—These claims are located in the southern portion of the district in sec. 30, T. 47 N., R. 2 E., N.M.P.M. Secondary uranium minerals occur locally in an outcropping of silicified nonbrecciate.. Dakota sandstone. The results of limited drilling have not established the presence of an ore body in the underlying Morrison or Precambrian rocks. Geologic mapping, based largely on float distribution in the surrounding area, defined a northwest-trending zone of silicified Dakota sandstone that separates nonsilicified Dakota sandstone from volcanics. To the southwest of this silicified zone, drilling has disclosed that rhyolitic tuffs have been dropped down more than 200 feet.

Approximately 1,000 feet of diamond core drilling has been completed on the La Rue No. 2 claim in the vicinity of the mineralized outcrop. The holes were drilled vertically and only a very small amount of core was recovered. Three out of five holes were entirely in altered rhyolitic tuff. The other two holes were drilled through similar material but were bottomed in silicified, fractured, weakly mineralized sandstone and mudstone of the Morrison(?) formation.

At these claims, secondary uranium minerals occurring at an isolated outcrop along a fault trace may be the oxidized surface expression of an ore shoot as at the Thornburg mine. Interpretation of surface mapping indicates a change in strike of the inferred fault near the mineralized outcrop; this condition coupled with an undetermined amount of strike slip may have furnished a control on the movement of uranium-bearing hydrothermal solutions.

The secondary uranium minerals uranophane, autunite and minor amounts of torbernite are present at the mineralized exposure as grain coatings and vug and fracture fillings. A minor amount of uraniferous asphaltite is also present.

This prospect is similar to the initial prospect at the Los Ochos claims in the following ways: a belt of silicified sedimentary rocks, at least 1,000 feet in linear extent, is interpreted to be a fault trace; ore-grade material outcrops locally; a similar secondary uranium mineral assemblage is present; there is evidence of two generations of invasion by hydrothermal solutions.

The similarities between the two properties suggest that the uranium minerals present at the La Rue claims were also precipitated from hypogene solutions. The outcropping of silicified upper Dakota sandstone is not brecciated and, in this respect, it is dissimilar to surface exposures at the Los Ochos claims. There appears to have been no significant movement along the fault zone after the initial invasion by silica-bearing hydrothermal solutions.

Other Prospects

Dissection along Cochetopa Creek has furnished good exposures of Precambrian granite and granite gneiss in the central and southern parts of the district. Several shear zones which cut these rocks in essentially an easterly trend are weakly mineralized. At the surface, these structures exhibit radioactivity of two to ten times background and are profusely stained by limonite and hematite. Assay results of samples from several of these mineralized shear zones range from 0.01 percent to 0.04 percent U_3O_8. No significant increase in radioactivity with depth was observed in the few mineralized structures of this type that have been drilled.

Equilibrium Relationships

At the Los Ochos, Kathy Jo and La Rue claims, samples from outcrops and surface cuts are generally in equilibrium or slightly in favor of chemical U_3O_8. Samples from underground workings at the Los Ochos and Kathy Jo claims are out of equilibrium in favor of chemical U_3O_8 by 10 to 50 percent with the majority in the 20 to 30 percent range. Samples from shear zones cutting Precambrian rocks in the central and southern parts of the district are out of equilibrium in favor of radiometric U_3O_8 over a wide range. The significance of these equilibrium relationships has not been established. Additional sampling would be necessary in order to have sufficient data to analyze this problem.

CONCLUSIONS

Origin of the Ore Deposits

In the Cochetopa mining district, faulting and related brecciation of sedimentary rocks have provided a favorable environment for localizing the precipitation of uranium minerals from ascending hydrothermal solutions.

The deposits at the Thornburg mine are classified as hypogene in origin and formed under epithermal conditions as defined by Lindgren (4). During the initial invasion of hydrothermal solutions moving upward along the Los Ochos fault, sedimentary rocks were silicified in an elongate zone parallel and adjacent to the fault. Intense silicification of the sedimentary rocks, contrasted with the absence of silicification in Precambrian rocks, suggests precipitation by wall rock control. The relative importance of chemical versus physical control warrants further investigation. Initial permeabilities of these rock types does not appear to have exerted a strong influence on the type of alteration that affected them. Sedimentary and crystalline rocks of widely varying composition and initial permeabilities have been uniformly subjected respectively to silicic and argillic alteration. Physically favorable environments for the precipitation of marcasite and pitchblende from later invasions of hypogene solutions were created when renewed movement on the fault resulted in locally intense brecciation and fracturing of the silicified sedimentary rocks along the Los Ochos fault.

At the Thornburg mine, the following observations indicate a hydrothermal origin of the ore bodies:

1) The lithology of the sedimentary host rocks was not the chief factor effecting the localization of the uranium minerals in ore shoots along the Los Ochos fault since sandstone and mudstone are essentially mineralized to the same degree. Irregular extensions of the ore zones in the Salt Wash sandstone member may be expected in unexplored areas north of the Los Ochos fault.[2] Silicification and subsequent fracturing, resulting in a favorable environment for localization of uranium minerals, probably extends farther from the fault into the sandstone than into the mudstone, because of the initial relative permeability of these two rock types.

2) The Los Ochos fault and related fracture and breccia zones controlled the emplacement of the two largest ore bodies, which are essentially vertically oriented with their greater dimensions parallel to the fault.

3) Extensive elongate zones of severe rock alteration, adjacent and parallel to the Los Ochos fault, form halos around the ore bodies. The argillic alteration of the crystalline rocks during the initial invasion of solutions resulted in an environment that was not as favorable for the emplacement of uranium minerals as the silicified and fractured overlying sedimentary rocks. The ore shoots are thus predominantly confined to the section of sedimentary rocks.

[2] Surface and underground exploration completed since the termination of the field investigations has disclosed that the lower Salt Wash member is continuously mineralized and is of commercial grade locally for at least 1,000 feet along the north side of the Los Ochos fault. This mineralized section extends as much as 500 feet northward from the fault.

4) In the Cochetopa mining district, the distribution of the Mancos shale suggests that it probably overlaid the Dakota sandstone in the vicinity of the Thornburg mine at the time of mineralization. That portion of the fault cutting the Mancos would have been relatively impermeable to migrating solutions. It appears unlikely that ground waters containing uranium released by erosion of volcanic rocks overlying the Mancos shale could have percolated downward along the fault and mineralized the underlying Morrison formation. The unimportance of lateral or downward migration of mineralizing ground waters is emphasized by the fact that there are no known bedded-type concentrations of uranium minerals in physically favorable lithologic units of the Morrison or Dakota formations.

The position of the ore bodies, the structural setting and the pattern of rock alteration are all spatially related to the Los Ochos fault system. From this evidence, it is concluded that the emplacement of the ore bodies and the observed related features resulted from mineralizing solutions of hydrothermal origin migrating upward along the fault conduit.

Two theories on the source of the uranium-bearing solutions have been considered:

1) Razor Dome, a local thickening of volcanic rocks about 4 miles southeast of the Los Ochos claims, and beyond the limits of the mapped area, may be a local eruptive center from which emanations of uranium-bearing solutions could have originated.

2) Uranium-bearing hypogene solutions may have been associated with late stages of Tertiary igneous activity postdating the extrusion of the flow sheets. On the north slope of Razor Dome, several stocks intrude volcanic rocks. Seven miles south of the Los Ochos claims, basic dikes cut volcanic rocks.

Most of the base-metal and precious-metal mining districts in the San Jaun volcanic province of southwestern colorado are spatially related to Tertiary igneous intrusions that cut the flow rocks. The intrusive centers and the ore deposits in this province are also presumed to be genetically related (1). Age-determination studies being made on samples from the Thornburg mine may aid in establishing the origin of the ore bodies with more certainty.

Criteria Relating to Localization of Uranium Minerals in the Cochetopa Mining District

1) Structure.—Intersections, splits, and changes in strike or dip of faults, especially where accompanied by brecciation of sedimentary rocks, physically control localization of uranium minerals. Faults in the vicinity of zones of contact between intruded granite and older metamorphic rocks should receive special attention. Faults cutting such transitional zones may be more deeply seated because of inherent structural weaknesses at this contact zone.

2) Stratigraphy.—The Morrison formation and Dakota sandstone contain the most favorable host rocks for the emplacement of uranium ore bodies. Significant amounts of uranium minerals are not present in the Mancos shale or in the volcanic flow rocks. In general, Precambrian rocks do not appear

very favorable, even though numerous shear zones cutting granite are mineralized and one of the ore shoots at the Los Ochos claims does extend a short distance into schist. Of these crystalline rocks, schist is relatively the most favorable host for the emplacement of uranium minerals from hydrothermal solutions.

3) Rock Alteration.—Along fault traces, rock alteration associated with anomalous radioactivity increases the favorability for a deposit. However, it has been observed that ore bodies lie within broad silicified zones which, in their peripheral portions, may be nearly barren of uranium minerals. Silicified sedimentary rocks along known or inferred fault traces that are not abnormally radioactive may be significant. The variegated mudstones of the Brushy Basin shale member will normally be bleached to a uniform gray to light-green color where affected by hydrothermal solutions. Outcrops may exhibit moderate limonite staining.

An understanding of what is considered a favorable environment for the localization of uranium minerals and a knowledge of features related to ore bodies may aid in the discovery of additional deposits in the Cochetopa mining district.

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PETROLOGY AND PREPARATION OF CERTAIN (PERMIAN) COAL SEAMS OF INDIA

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ABSTRACT

The petrological characteristics of many of the Permian coal seams of India have a profound and particular influence upon their preparation and utilization properties. Relatively high proportions of ash are largely derived from the finely dispersed sedimentary mineral matter generally present in all coal types. The proportions of the clastic minerals generally increase with those of the "inert" seam constituents and are thus generally greatest in the common "dull" coals. The intimate association of fine mineral matter and "inert" organic constituents in both macroscopic and microscopic bands makes the problems of preparation more difficult.

Reduction in the proportions of clastic mineral matter inevitably lowers the content of the "inerts" and thus increases those of the "coking" constituents. Consequently the characteristics of the coke produced vary considerably with the degree of cleaning achieved on the coal. Substantial reduction in the clastic mineral content of the coal charge could be accompanied by significant deterioration in the mechanical strength of the coke produced.

INTRODUCTION

In common with the coal producing and consuming industries of the rest of the world, those of India during the past three or four decades have been faced with a number of increasingly serious and related problems. The depletion of reserves of best quality fuels together with the enforced and more highly mechanised development of inferior seams has resulted in serious deterioration in overall product quality and focussed attention upon the prospects of beneficiation.

As to the economics and practicability of producing significant improvement in quality of Indian coals by mechanical methods of beneficiation, opinions in India have been greatly divided. As a result of the considerable amount of research undertaken between 1918 and 1945 it was generally agreed that the Gondwana (Permian) coals of India in common with those of South Africa, differed in a number of respects from the Carboniferous seams of the northern hemisphere. These differences appeared more especially in the character and distribution of the mineral matter. In addition to the usual cleat ash, rock or stone bands and partings, the Indian coal seams commonly contained significant proportions of dispersed sedimentary mineral matter intimately associated with the organic constituents of the seam. To reduce substantially the proportions of such mineral was recognized as being potentially very difficult, but the general pessimism regarding prospects for beneficiation was not shared by the Tata Iron and Steel Company. In the light of study results obtained in their own laboratories as well as those of the Geological Survey of India

and the Indian School of Mines, Dhanbad, the Tata authorities were confident that significant and economic improvements in quality could be achieved on an industrial scale. Whereas other groups had assessed the cleaning potential of the Indian coals by reference to the relatively low ash standards expected in European and American practice upon Carboniferous seams, the objectives of the Tata project were much more realistically related to the actual inherent mineral-ash characteristics of the Indian seams. Under optimum conditions of extraction and without beneficiation other than hand-picking, the best of the seams formerly exploited (1920) had yielded coal of 9 to 14 percent ash. On the basis of the study results it was considered economically practicable to produce by beneficiation of the plus $\frac{1}{4}''$ sizes a clean coal of 14 to 15 percent ash with middlings of 28 to 30 percent, from inferior seams in which the mean ash content as mined exceeded 20 percent.

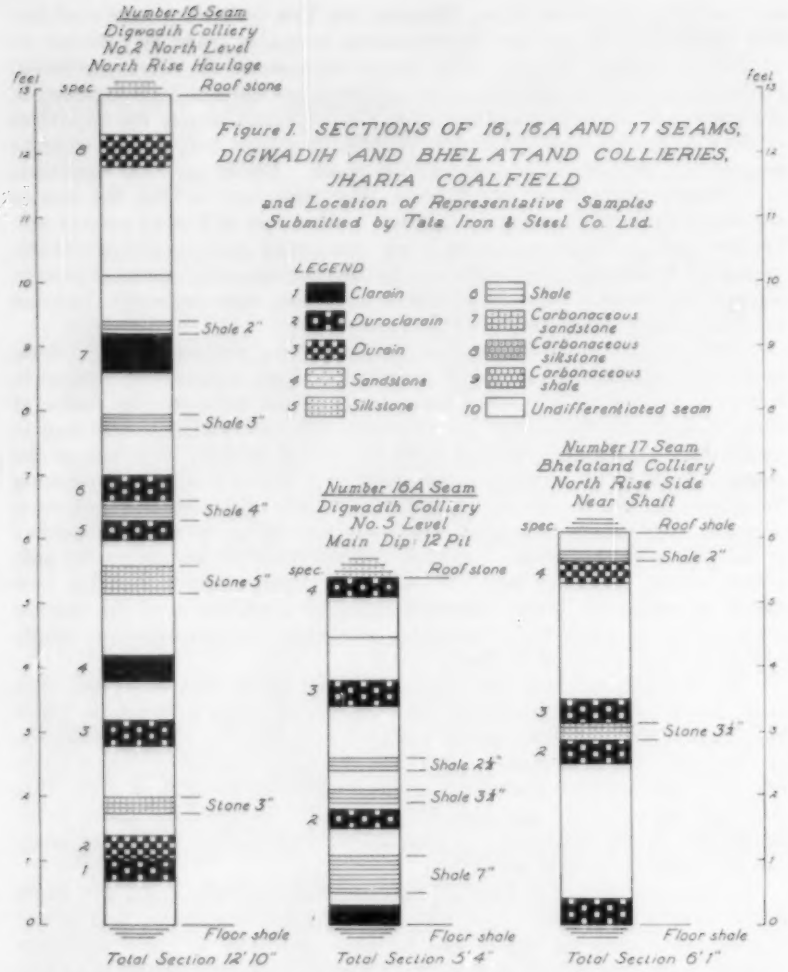
After examination of the various cleaning systems available and experience of the then current South African practice, the Tata organization ordered in late 1946 and early 1947 two Chance heavy media units for installation at West Bokaro and Jamadoba. At this same time, the author was invited to undertake a detailed petrological study of selected samples of certain of the seams as a basis for independent evaluation of the possibilities of reducing the overall content of mineral ash and the probable effects of such a decrease upon the properties of the coals. The major part of this work was completed in the latter part of 1948 and, together with the results of certain further subsidiary studies, forms the basis of this paper. Delay in publication has been due to a number of factors including extended examination of the original samples and the completion of a number of related investigations upon closely comparable coal seams of Australia.

The two Chance heavy media units installed by the Tata Company have now been in successful operation for a number of years with results which are in full accord with those anticipated on the basis of the various laboratory and industrial research studies (3). The foresight, interest in critical scientific study and accurate assessment of the situation by the officers of the Tata Iron and Steel Co. Ltd. has been fully justified. To them the author is indebted both for the opportunity of undertaking a particularly interesting study and permission to publish the results.

Comparative studies of Permian coal seams of Australia, India and South Africa have demonstrated close affinities in physical constitution and related characteristics such as would indicate close similarity in their utilization features. The results embodied in the present paper are potentially of interest to the coal producing and consuming industries of each of these countries.

GENERAL

The Permian coal seams of India constitute one of the most important mineral resources of that country. The properties of the coal seams and the geology of the coalfields have been the subject of a number of important papers and monographs including those by Simpson and Ball (30), Jowett (15), Fermor (4, 5), Gee (12, 13), Bannerjee (1), Fox (7, 8, 9, 10), Forrester (6)



and Ganju (11). Farquhar (3) has provided a most effective discussion of the problems of beneficiation of the Damodar Valley coal seams and described methods applied successfully to their solution.

The general concensus of opinion appears to be that the Permian coal seams were formed under freshwater conditions and are generally of allocthonous origin. As regards the environment of deposition, opinions differ. The circumstance that many of the Gondwana formations and areas of deposition occur in "basins" that are commonly related to present day river valleys and preserved as a result of tectonic disturbance, has been considered signifi-

cant. Oldham (26) postulated deposition of the Gondwana formations in river valleys; Fox (8, 10) favoured a lacustrine origin, probably in rift valleys; Ganju (11) considers that they are more probably of deltaic deposition.

The coal seams are almost invariably characterized by relatively high proportions of sedimentary mineral matter and subject to rapid lateral and vertical variation.

The coal seams for examination were selected from those of the Damodar Valley coalfields of Bihar, which contribute by far the greatest proportion of the total Indian coal production. Those selected were the 16, 16A and 17 seams of the Jharia coalfield; the Kargali seam of the Bokaro field; and the Argada Top, Sirka Bottom and Sirka Top seams of the South Karanpura district. As these seams varied from 5 to more than 60 feet in thickness, it was quite impracticable to undertake detailed petrological examination of

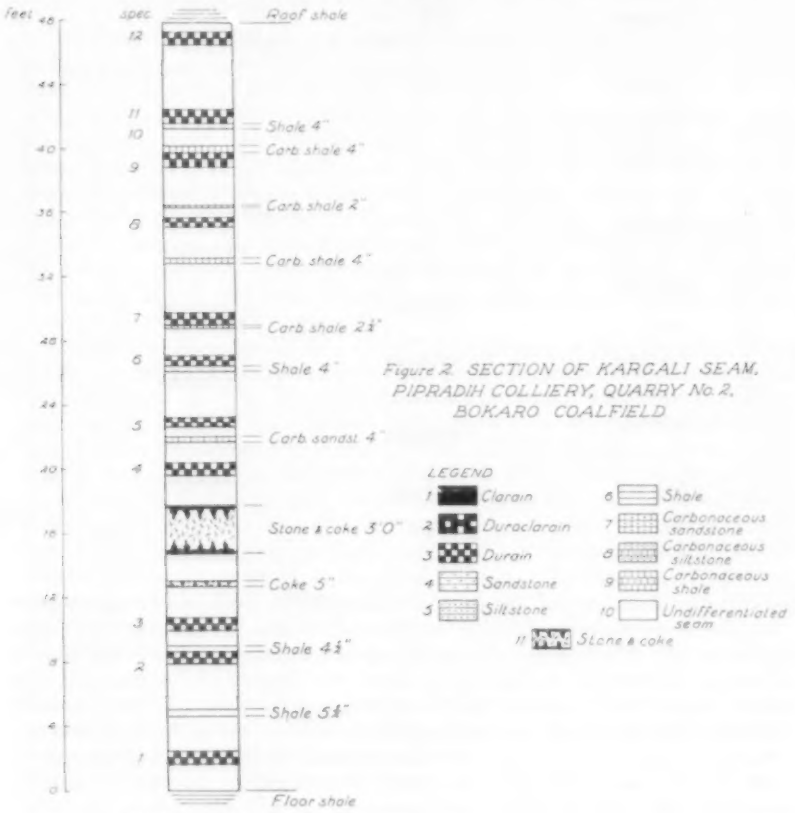


Figure 2. SECTION OF KARGALI SEAM, PIPRADIH COLLIERY, QUARRY No. 2, BOKARO COALFIELD

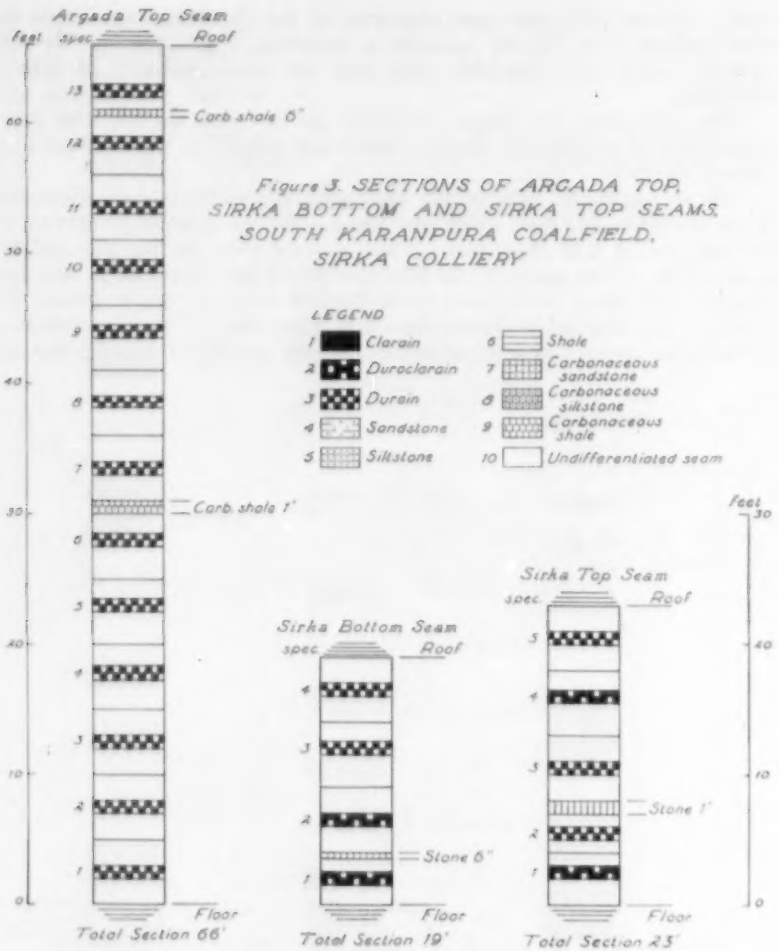


Figure 3. SECTIONS OF ARGADA TOP, SIRKA BOTTOM AND SIRKA TOP SEAMS, SOUTH KARANPURA COALFIELD, SIRKA COLLIERY

their entire thickness and attention was consequently confined to representative samples selected in the field by experienced officers of the authorities concerned. The distribution and overall macrotype of the samples in the various seams is represented in Figures 1, 2 and 3. The limitation imposed upon the scope of the studies through necessarily incomplete sampling must be considered as qualifying the results obtained, but in view of the essential community of character revealed and subsequent satisfactory preparation experience on the industrial scale, the study limitations in the present instance evidently were not of serious consequence.

According to Fox (10) the general Lower Gondwana succession in the Peninsula of India may be summarized as follows:

Lower Trias (Bunter)	Panchet Series	Damudas	Lower Gondwanas (Glossopteris flora)
Upper Permian	Raniganj Series		
Middle Permian	Barren Measures		
Lower Permian	Barakar Series with Karharbari stage and Umaria marine beds		
Upper Carboniferous	Talchir Series with glacial boulder beds		

Within this succession the Barakar and Raniganj Series are significantly coal bearing, the former constituting the most important Coal Measures in India. All the seams examined in this present study were from the Barakar Series.

THE JHARIA, BOKARO AND SOUTH KARANPURA COALFIELDS

While it is unnecessary for present purposes to consider in detail the geology of the various coalfields, certain aspects of the environment and general characteristics of the seams are of immediate interest.

In each of the three coalfields concerned the Baragar or Lower Coal Measures are much the more important, the seams of the Raniganj Series being of decidedly minor significance. The Barakar seams and sediments of these three Damodar Valley fields exhibit considerable variation and with the exception of those of the South Karanpura district are much disturbed by faulting. Sill and dike intrusion is common (mica peridotites and dolerites), the former commonly resulting in the considerable development of natural coke or cinder coal (the local "jhama") when injected into or closely adjacent and parallel to the coal seams.

It has been recorded by Fox (8, 10) that in each of the Damodar Valley coalfields, and particularly in those now under discussion, the quality of the Barakar seams generally deteriorates towards the west. Similarly, comparing the Barakar coals of the different fields there is a definite thickening and deterioration of the seams towards the west, in which direction they generally tend to split and pass into carbonaceous shales. It has also been generally observed that the fine fractions of the mined coal may contain 2 or three percent less ash than large coal from the same seam, a result of the preferential breakage oi the more tender "bright coal" (vitrains and clarains) generally characterized by lower contents of clastic mineral matter. The chemical composition and range of variation exhibited by the coal ash is in accordance with the general domination of sedimentary mineral matter in the seam.

In the Jharia coalfield, the majority of the Barakar coals are considered as coking, especially those occurring above the 9 seam (numbered in ascending succession). Eighteen seams aggregating 200 feet of coal are being worked in the Barakar Series: total available reserves to a depth of 2,000 feet have been estimated as 4,500 million tons (7, 10).

In the Bokaro coalfield, twenty-nine coal seams are recorded of which nineteen exceed four feet in thickness (10). Most of the operations have

hitherto been confined to the Kargali seam of the eastern districts in which it varies from 40 to more than 100 feet in thickness. Reserves in this single seam of high-ash coking coal approach 500 million tons.

In the South Karanpura coalfield a number of seams occur that aggregate almost 300 feet in thickness. Of these the Sirka and Argada seams are most prominent, ranging in thickness between 20 and 85 feet. Total coal reserves to a depth of 2,000 feet have been estimated as between 5,000 million and 10,000 million tons (10).

Comparing the Barakar succession and seams in the three coalfields under discussion, it has been suggested that the Sirka seams of South Karanpura may be correlated with the Kargali seam of Bokara which in turn may represent the 11 and 12 seams of Jharia. In view of the nature of the known formational variations and general difficulties of seam correlation such proposals are regarded as highly tentative (10).

METHODS AND TECHNIQUES USED IN THE INVESTIGATION

To make their most effective contribution to the solution of problems of coal preparation and utilization, it is essential that qualitative and quantitative petrological studies should be integrated as closely as possible with other appropriate methods of physical and chemical examination. For these purposes macropetrological examination alone is generally inadequate and must be supplemented by methods of micropetrological analysis, which will yield results of adequate accuracy without disproportionate commitments of time and labour.

The methods of petrological analysis employed vary with the personal preference and experience of the investigator as well as the scope and purpose of the examination. To attempt the detailed, serial micrometric analysis of the full section of a thick seam of coal would normally be completely uneconomic of time and effort in relation to the possible value of the results obtained. Consequently, various authorities have evolved different "compromise" methods of microscopic analysis designed to suit the particular kind of study upon which they are engaged. Serial thin sections, serial polished blocks, polished and thin section preparations of particular or representative granulated coal samples have all been used individually and in conjunction to obtain quantitative micropetrological data by Stach (31, 32, 33, 34), Cady (2), Makowsky and Abramski (17), Schopf (29), Parks (28), Parks and O'Donnell (27), Kuhlwein and Hoffman (16). All methods of petrological coal analysis are subject to limitations not only because of the technical problems of making the analyses, but also as a result of the inherent and potentially considerable variation in the physical and chemical properties of the various groups of constituents that optically appear almost identical (18, 20, 21, 22).

For the limited purposes of the present study the petrological examination and analyses of the representative samples were made according to a combination of methods that have proved satisfactory over a period of many years.

From the representative block samples supplied for the purpose of this study, four thick slices were cut by diamond saw, each perpendicular to the

bedding and the full thickness of the original sample. The adjacent faces of two of these slides were used in the production of serial thin and polished sections, which in consequence could be directly related to each other and used for both macro- and microscopic analysis. Of the remaining slices, one was used in block ashing tests to produce "skeletographs" from which valuable information could be obtained regarding the distribution of the ultra-fine mineral constituents of the seam. The remaining slice was held in reserve as material for special tests including specific gravity separations.

Experience has shown that not only the proportions, but also the size and distribution of both the macerals (organic constituents) and mineral ingredients of the coal are of importance in determining preparation and utilization characteristics, particularly the coking properties. Consequently, the methods of micrometric analysis employed must permit reasonable evaluation of both the constituents and the coal types.

Within the range of acceptable errors and limitations this was achieved quite simply and with moderate expenditure of effort. On the basis of a preliminary microscopic examination of both thin and polished sections, portions of each original block were selected as representative for detailed micrometric analysis in thin and polished section. In view of the evident, wide and inherent variations exhibited by macerals that are optically closely comparable or identical, it is considered that no great error in micropetrological analysis is introduced by referring the seam constituents to four main groups, namely (i) vitrain or vitrinite (including translucent attritus of Theissen) (ii) fusain or fusinite (including all organic "inerts" such as fusain, sclerotinite and micrinite) (iii) exinite (including spores, cuticles and optically comparable resin-like materials of doubtful chemical character), and (iv) mineral matter. The various "intermediates," of which a large proportion certainly fall within the normal range of variation of the dominant coal constituents vitrinite and fusinite, are included with one or other of these respective groups as appears most appropriate. Difficulties of discrimination do arise but are not considered likely to introduce significant errors particularly in view of the large number of observations made.

The analyses are made by the simple method of linear intercepts in a direction perpendicular to the bedding of the coal, using a binocular petrological microscope with a 8 mm objective and eyepieces of magnification × 10, one of which is fitted with a scale. In the course of the analysis, the individual thickness of each constituent particle in a direction perpendicular to the bedding is recorded in the appropriate maceral group; no arbitrary discrimination is made between optically identical materials solely on the basis of maceral size. Each section traverse is recorded continuously throughout a single coal macro- or micro-type layer. When a change of coal type occurs, the traverse is continued but a new series of records is begun and continued to the boundary marking a further change in the coal type. From these records it is a simple matter to extract much relevant data including (i) the volumetric proportions and mean particle size of each of the constituent maceral groups in the various coal types and (ii) the mean thickness, volumetric proportions and distribution of the coal types in the original sample (Tables 1, 2).

For ease of reference coal types containing 70 percent or more of vitrinite are regarded as clarain; those with more than 50 percent of the "inerts" (fusinite and micrinite) are considered as durain. Between these two (less than 50 percent "inerts" or 70 percent vitrinite respectively) the coal is regarded as duroclarain (Tables 1, 2; Pl. 1, 2). Anomalies arising from this simple classification have so far proved to be of only very minor importance.

Table 1. Detailed micrometric analyses of selected representative coal type samples.

Seam and locality	Section	Microtype constitution by microtype					Microtype constitution by maceral and mineral							
					Mean layer thickness (mm)		Vitrain (Vitrinite)		Fusain (Fusinite) + Micrinite		Exinite		Visible mineral matter	
		Selected macrotype (part only of section)	Microtype (uniform)	Vol. proportion %	Individual microtypes	Grouped microtypes	%	Mean thickness (mm)	%	Mean thickness (mm)	%	Mean thickness (mm)	%	Mean dimension (mm)
No. 17 seam Sheletand Coll. Jharia Coalfield	3	DUROCLARAIN	Duroclarain Duroclarain	100	10.3	10.13	67 61	0.020 0.041	32 38	0.092 0.051	1 1	0.002 0.004	1 1	0.036
No. 16A seam Digwadih Coll. Jharia Coalfield	1	CLARAIN	Clarain	100	17.21	17.21	74	0.063	25	0.025	1	0.005	1	0.018
No. 16 seam Digwadih Coll. Jharia Coalfield	4	CLARAIN "B"	Clarain Clarain Durain	82 18	9.89 4.45	8.08	83 70 41	0.161 0.113 0.057	16 29 56	0.031 0.069 0.041	1 1 1	0.003 0.003 0.002	1 1 2	0.017 0.026
	3	CLARAIN "AB"	Clarain Clarain Clarain	100	6.86	6.86	92 88 72	0.188 0.114 0.117	7 12 26	0.012 0.002 0.046	1 1 1	0.002 0.003 0.002	1 1 2	0.020 0.018 0.021
	1	DUROCLARAIN	Clarain Clarain Duroclarain Durain	48 41 11	5.23 9.13 2.47	5.51	72 73 61 45	0.069 0.046 0.053 0.027	27 25 36 50	0.033 0.021 0.013 0.028	1 1 1 1	0.002 0.002 0.003 0.002	1 2 2 5	0.013 0.018 0.040 0.048
Kargali seam Pipradih Coll. Bokaro Coalfield	5	DURAIN	Durain Durain	100	9.18	9.18	17 38	0.022 0.025	82 61	0.118 0.052	1 1	0.002 0.002	1 1	0.080 0.029
	2	DURAIN	Durain	100	19.33	19.33	39	0.038	60	0.052	1	0.003	1	0.002
Top seam Sirka Coll. South Kurasmure coalfield	5	DUROCLARAIN	Clarain Clarain Clarain Duroclarain Duroclarain	62 38	2.55 8.46	4.98	86 88 72 68 58	0.069 0.057 0.060 0.041 0.034	11 11 23 31 38	0.016 0.006 0.016 0.030 0.021	3 1 1 1 1	0.002 0.003 0.004 0.002 0.003	3 4 4 1 4	0.026 0.016 0.031 0.019 0.025
	1	DURAIN	Duroclarain Durain Durain	25 75	5.21 7.95	7.02	68 58 25	0.063 0.047 0.041	30 39 73	0.033 0.032 0.074	1 1 1	0.003 0.004 0.003	1 3 2	0.027 0.030 0.032
Bottom seam Sirka Coll. South Kurasmure Coalfield	4	DURAIN	Duroclarain Durain Durain Durain	8 92	2.03 7.67	6.22	50 48 16 35	0.028 0.020 0.019 0.028	45 51 80 62	0.018 0.041 0.042 0.028	3 1 1 1	0.006 0.003 0.002 0.003	2 2 3 2	0.022 0.020 0.027 0.018
	3	CLARAIN	Clarain Clarain Duroclarain	81 19	9.33 4.61	7.76	82 71 67	0.082 0.055 0.041	17 28 33	0.026 0.029 0.021	1 1 1	0.003 0.003 0.002	1 1 1	0.027 0.024 0.018
Argada Top seam Sirka Coll. South Kurasmure Coalfield	12	DUROCLARAIN	Clarain Duroclarain Duroclarain Duroclarain Duroclarain Duroclarain Duroclarain	1 99	0.25 3.11	2.70	90 66 58 69 55 58 68	0.114 0.024 0.030 0.031 0.028 0.034 0.047	10 27 34 26 39 39 27	0.008 0.007 0.012 0.021 0.025 0.022 0.023	1 7 8 5 2 1 2	0.003 0.005 0.004 0.004 0.002 0.003 0.004	1 2 4 1 4 1 3	0.016 0.017 0.019 0.012 0.006 0.022 0.015
	7	DURAIN	Duroclarain Durain Durain Durain Durain	18 82	3.15 3.78	3.66	54 47 34 37 39	0.044 0.031 0.029 0.023 0.028	46 46 64 63 60	0.042 0.026 0.034 0.054 0.041	1 7 2 1 1	0.003 0.004 0.003 0.003 0.002	1 1 1 1 1	0.017 0.048 0.032 0.018 0.015
	1	DURAIN	Durain Durain Durain Durain	100	4.13	4.13	46 26 49 31	0.011 0.011 0.026 0.023	52 74 51 68	0.029 0.037 0.026 0.033	1 1 1 1	0.003 0.003 0.002 0.003	2 1 1 1	0.018 0.014 0.025 0.012

Table 2. Collective maceral constitution of selected macrotype samples and character of coke produced (free swelling)

Seam and Locality	Macrotype	Collective micrometric proportions (macerals) Recalculated to 100% total Vitrinite + Exinite	Fusinite + Micrinite	[illegible]	Ratio Coke vol. Coal vol. (free swelling)	Coke Character
Number 17 Seam	1. Vitrain	100	0	3.7	½	Coarsely cellular; tender.
Bhelatand Colliery	2. Clarain	80.9	19.1	11.5	2½	Finely cellular; strong
Jharia Coalfield	3. Durain	37.7	62.3	17.0	1	Feebly coherent; very friable
Number 16A Seam	1. Vitrain	100	0	3.4	½	Coarsely cellular; tender.
Digwadih Colliery	2. Clarain	75.0	25.0	9.4	2	Compact, cellular; strong.
Jharia Coalfield	3. Durain	41.4	58.6	17.0	1	Friable.
Number 16 Seam	1. Vitrain	100	0	4.5	½	Coarsely cellular; tender. [illegible]
Digwadih Colliery	2. Clarain A	55.0	15.0	9.1	3½	Coarsely cellular; tender.
Jharia Coalfield	3. Clarain B	70.8	29.2	11.9	2½	Finely cellular; moderately strong.
	4. Duroclarain	67.3	32.7	14.4	2	Compact; cellular strong.
	5. Durain A	47.2	52.8	15.2	1	Compact; slightly friable.
	6. Durain B	34.4	65.6	31.7	1	Coherent; friable.
Kargali Seam	1. Vitrain	100	0	4.4	½	Coarsely cellular; moderately strong.
Pipradih Colliery	2. Clarain	80.9	19.1	15.4	2½	Finely cellular; strong.
Bokaro Coalfield	3. Duroclarain A	65.3	34.7	19.9	2	Finely cellular; strong.
	4. Duroclarain B	63.5	36.5	15.4	2	Compact, cellular; strong.
	5. Durain A	46.0	54.0	14.9	1½	Very compact; strong.
	6. Durain B	28.5	71.5	20.2	1	Coherent.
Top Seam Sirka Colliery	1. Duroclarain A	69.0	31.0	13.0	1	Coherent.
	2. Duroclarain B	60.5	39.5	14.1	1	Feebly coherent
South Kurenpura Coalfield	3. Durain	46.0	54.0	16.9	1	Very friable
Bottom Seam Sirka Colliery	1. Duroclarain A	65.5	34.5	5.6	1½	Coherent
	2. Duroclarain B	57.3	42.7	9.0	1	Feebly coherent
South Kurenpura Coalfield	3. Durain	38.2	61.8	12.6	1	Very friable
Argada Top Seam	1. Clarain	89.6	10.4	5.9	1	Very compact; finely cellular; fairly strong.
Sirka Colliery	2. Duroclarain	68.0	32.0	20.9	1	Feebly coherent.
South Kurenpura Coalfield	3. Durain	38.8	61.2	15.5	1	Very friable.

By careful comparison, these relatively few analyzed representative thin and polished sections can be used with reasonable confidence to evaluate the nature and constitution of all other samples of the same seam. Such a classification is not adequate to deal with all possible variations but it has the merit of simplicity and has been proved effective in the great majority of petrological studies in which it has been used.

In one particular respect, this method of micropetrological assessment has proved to be inadequate, namely in determining the proportions and distribution of the sedimentary mineral matter. To be detected and measured in the thin and polished sections, the mineral grains should in general be larger than 5 microns in mean dimensions unless in high concentration in well defined silt or shale bands. As a large proportion of the sedimentary mineral is of much

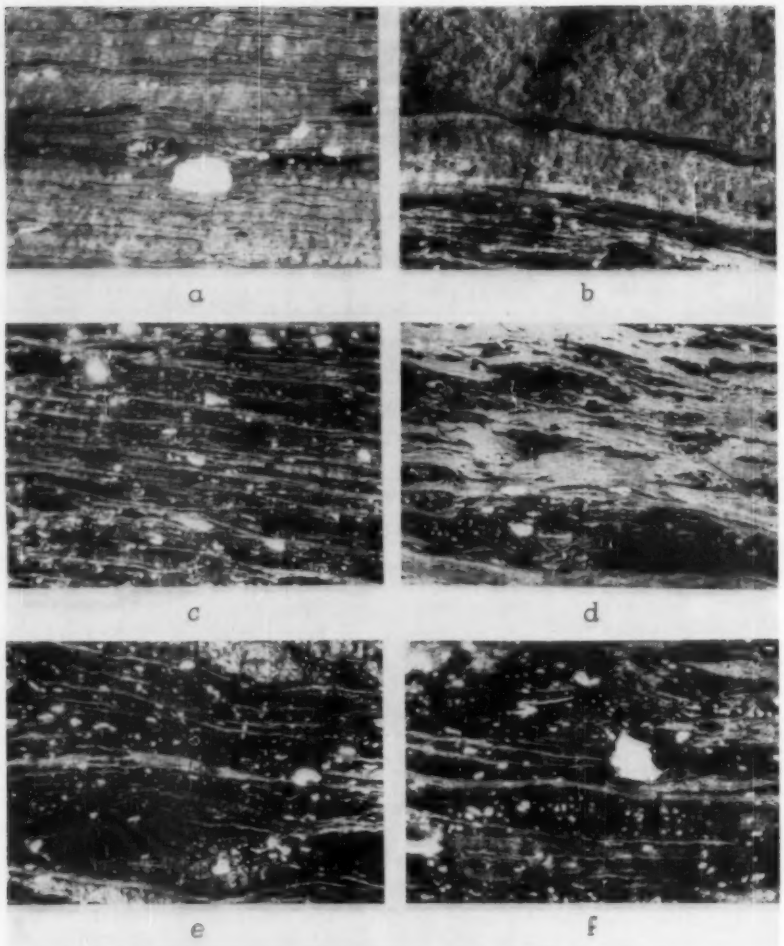


PLATE 1. Coal microtypes of seams of the Damodar Valley coalfields of Bihar. Low to medium ash content. × 140.

(a) Clarain, 16A seam (Jorapukhar), Digwadih Colliery, Jharia Coalfield: Thin sheets of vitrinite, fusinite, compact and granular micrinite, "intermediates," sclerotinite and resin-like bodies; dispersed grains of quartz and other clastic minerals.

(b) Clarain–Duroclarain, 17 seam, Bhelatand Colliery, Jharia Coalfield: Clarain of coarse vitrinite sheets separated by thin layer of granular micrinite; abrupt transition to duroclarain of "shredded" vitrinite fragments with "intermediates," micrinite and some clastic mineral matter.

(c) Duroclarain, 16 seams, Digwadih Colliery, Jharia Coalfield: Fine sheets of vitrinite, small fragments of fusinite, granular micrinite and "intermediates"; dispersed clastic mineral matter in considerable proportions.

finer grade, commonly interstitial to the macerals and intimately dispersed throughout the microclastic coal types, it almost inevitably escapes observation.

It is in this particular connection that the "skeletographs" produced by slow ashing of suitable coal slices are particularly valuable (Pl. 3, 4). One of the originally prepared coal blocks or slices of $\frac{1}{4}''$ to $\frac{1}{2}''$ in thickness cut perpendicularly to the bedding and of suitable area (normally of the order $6'' \times 2''$) is brought slowly to a temperature of approximately 700° C over a period of not less than 30 hours and ashed to constant weight. Throughout the process, the specimen must be protected from appreciable air disturbance and mechanical shocks such as would disturb the fine, low density ash grains. By direct comparison with the polished and thin sections a great deal of useful information may be obtained regarding mineral character and distribution. The technique can be used very effectively on a quantitative basis.

Although not required in the original study, all possible or appropriate samples were later analyzed chemically (Tables 4–10) to supplement and assist in the interpretation and application of the petrological study results. In addition special samples were selected on a petrological basis, to demonstrate the range of variation of the coking characteristics of the different coal types present in each seam and assess the possible effects of preparation upon this property (Tables 4–11, Figs. 9–11, Pl. 5–7). A number of selected samples were also submitted to specific gravity separations as a guide to the possible ash reduction which might be achieved in practice.

It will be appreciated that the objectives of this study were limited both as regards intention and the particular circumstances prevailing. Nevertheless, the results obtained considered in relation to subsequent industrial experience demonstrate the considerable potential value of such simple and economic methods of laboratory investigations.

PHYSICAL AND CHEMICAL CHARACTERISTICS OF THE REPRESENTATIVE SAMPLES

General

The community of character exhibited by many of the Permian coal seams of India, Australia and Africa has already been recorded together with certain broad similarities and differences which they exhibit as compared with Carboniferous seams of the northern hemisphere (19, 23). The important constituents vitrain or vitrinite (anthraxylon); fusain or fusinite, "intermediates" and micrinite (fusain, brown matter, opaque attritus and granular opaque matter) are closely comparable in their origins, manner of occurrence and

(d) Duroclarain-Durain, Sirka Bottom seam, Sirka Colliery, Karanpura Coalfield: Irregular, "shredded" sheets of vitrinite, fusinite, "intermediates" and granular micrinite; some mineral in clastic grains and occupying cell spaces in fusain.

(e) Durain, 16 seam, Digwadih Colliery, Jharia Coalfield: Fusinite, micrinite and "intermediates" with fine vitrinite sheets; dispersed clastic mineral matter in quite considerable proportions.

(f) Durain: Fusain, fusinite, micrinite and "intermediates" with fine vitrinite sheets and irregular fragments; mineral in clastic grains and cell spaces of fusain in considerable proportions.

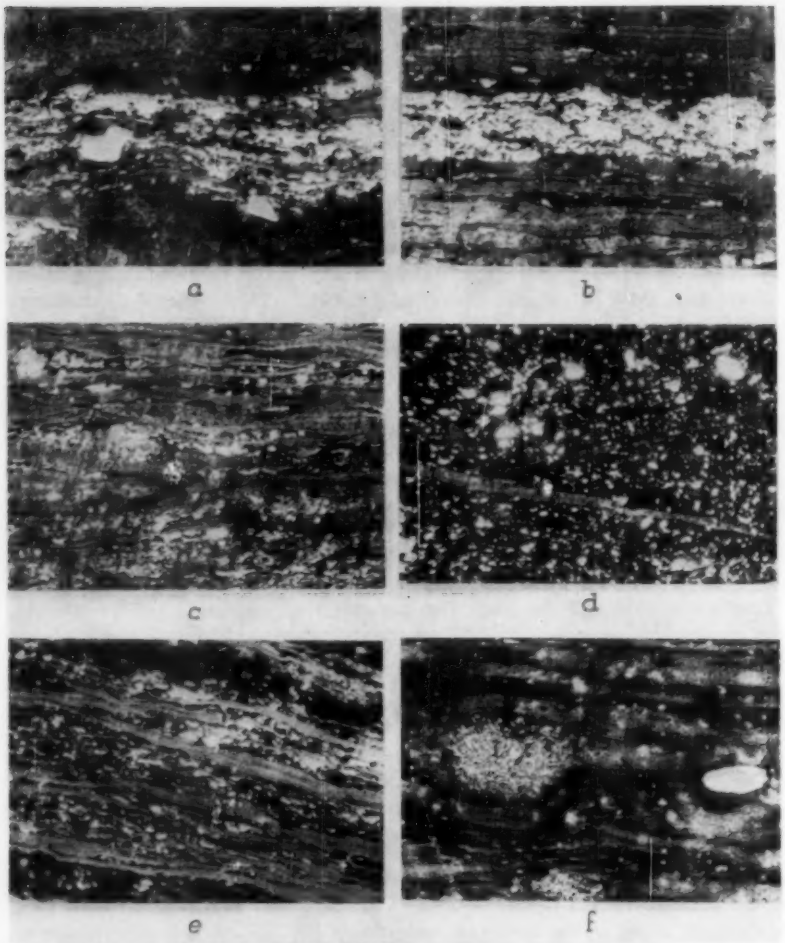


PLATE 2. Coal microtypes of seams of the Damodar Valley coalfields of Bihar. High ash content. × 140.

(a) Clarain, Argada Top seam, Sirka Colliery, Karanpura Coalfield: Microband of clastic mineral matter with a small proportion of thin vitrinite sheets, "intermediates" and micrinite, occurring in relatively coarse clarain.

(b) Clarain, 16A seam, Digwadih Colliery, Jharia Coalfield: Microband of clastic mineral matter with granular micrinite, occurring in a fine clarain.

(c) Clarain, Argada Top seam, Sirka Colliery, Karanpura Coalfield: Clastic mineral grains and micrinite distributed along numerous bedding planes between adjacent vitrinite sheets.

(d) Durain, Kargali seam, Pipradih Colliery, Bokaro Coalfield: Clastic mineral grains in "matrix" of micrinite, "intermediates" and rare vitrinite.

PLATE 3. Typical ash "skeletographs" formed by slow, controlled ashing of coal blocks. (a) Kargali seam, Pipradih Colliery: Section 3: Durain with overall ash content 9.8 percent. Pale grey-cream light and incoherent ash, with minute rust-brown spots representing original iron mineral. (b) Number 16 seam, Digwadih Colliery: Section 8: Clarain–Duroclarain–Durain–Carbonaceous Shale (descending order) in strongly banded coal, with overall ash content of 30.6 percent. Buff to grey-white ash with more compact, darker bands representing the high ash durain and carbonaceous shale bands.

range of variation in physical and chemical constitution in the Carboniferous and Permian seams respectively (19, 21, 22). Similarly, macrospores, microspores and cuticle material (exinite) as well as resins, resin-like and algal bodies normally occur as relatively subordinate constituents. Differences in the respective floras and possible environments of the Carboniferous and

(e) Durain, Sirka Top seam, Sirka Colliery, Karanpura Coalfield: Clastic mineral matter and micrinite concentrated in thin bands between thin vitrinite sheets and fusain fragments.

(f) Duroclarain, Kargali seam, Pipradih Colliery, Bokaro Coalfield: Microconcretions of carbonate mineral in series of alternating vitrinite sheets and micrinite layers.

Permian are represented by certain detailed structural, morphological and degradation characteristics in the coal seam constituents and coal types (19, 11). In general the plant entities of the Permian seams appear to have been more effectively disintegrated.

The coal types of the Permian seams of the Damodar Valley of India are broadly comparable with those of the Carboniferous of America and Britain but certain differences do emerge. In general they are characterized by a relatively fine state of maceral division (Pl. 1, 2, Table 1) and the presence of significant proportions of sedimentary mineral matter, commonly finely dispersed and intimately associated with the organic seam constituents even

PLATE 4. Typical ash "skeletographs" formed by slow controlled ashing of coal blocks. (a) Number 17 seam, Bhelatand Colliery: Section 2: Duroclarain with overall ash content of 12.8 percent. Pale grey, light and incoherent ash, with heavy brown staining due to pyrite. (b) Number 17 seam, Bhelatand Colliery: Section 4: Durain with overall ash content of 31.3 percent. Pale buff grey, coherent ash in which is evident banding representing changes in the mineral "sedimentation" characteristics.

Table 3. Size frequency distribution of visible micro-clastic mineral in principal coal types together with mean ash contents.

Coal Type	Frequency proportions (per cent) of mineral particles in various size ranges measured in microns (based upon 50,000 measurements)									Mean Ash Content (per cent)
	<10	10–20	20–30	30–40	40–50	50–100	100–150	150–200	>200	(mean of 77 determinations)
Clarain	48.2	27.2	10.8	4.4	2.8	6.0	0.4	0.2	-	8.8
Duro-clarain	50.9	23.9	7.6	4.7	2.8	6.9	1.9	0.9	0.4	14.3
Durain	45.1	21.8	11.5	5.5	3.8	8.1	2.4	0.8	1.0	20.7

Table 4: Chemical Analyses NUMBER 16 SEAM: DIGWADIH COLLIERY

Sample Number	Bulk Sample Identification	Moisture % A.D.coal	Ash % A.D.coal	% Dry, ash-free basis						% Dry basis				Swelling Number	Selected Type Samples	
				V.M.	C	H	N	S	O	Total S	Sulph. S	Pyr. S	Org. S		Sub-maceratype	Ash % A.d. coal
8	"Durain"	2.4	30.6	35.9	80.6	5.5	1.6	1.8	10.5	1.21	0.01	0.07	1.13	6½	Clarain	6.5
															Duro-clarain	13.6
															"Clarain"	35.5
															Carbon:Silt	44.7
															Carbon:Silt	50.3
7	Clarain	2.5	10.8	34.5	80.8	5.2	1.6	1.2	11.2	1.03	0.04	0.03	0.96	8	Clarain	8.8
															Duro-clarain	16.1
6	Duro-clarain	-	-	-	-	-	-	-	-	-	-	-	-	-	Clarain	11.8
															Duro-clarain	21.3
5	Duro-clarain	2.1	13.3	33.2	82.0	5.0	1.4	1.4	10.2	1.06	0.02	0.08	0.86	5½	Duro-clarain	14.4
4	Clarain	2.2	9.2	31.2	81.2	5.6	1.5	1.1	11.4	0.97	0.07	0.07	0.83	7½	Clarain	9.1
3	Duro-clarain	2.1	28.3	39.3	81.9	5.2	1.7	0.6	10.6	0.48	0.07	0.14	0.27	4½	Clarain	11.9
															Durain	15.2
															"Durain"	38.2
2	Durain	2.3	19.1	32.2	81.1	5.3	1.7	0.8	11.1	0.67	0.05	0.09	0.53	3	Durain	21.0
															Durain	28.7
1	Duro-clarain	2.1	12.7	32.4	81.0	5.3	1.7	0.5	11.5	0.43	0.07	0.04	0.32	8	Duro-clarain	9.1
															"Durain"	31.7

in relatively low ash coal (Pl. 1–4). In addition, minor proportions of pyrite and carbonate minerals occur normally in the joint planes, as micro-concretions (particularly in the "bright" coals) and occupying all cavities in the fusain bodies.

Initially, it was considered possible that the sedimentary mineral suite or assemblage might exhibit significant differences of constitution in the various coal types, but such differences proved to be relatively minor. The following

clastic minerals were observed in the various samples, their proportions being broadly related to the coal type:

Quartz Chalcedonic silica Felspar Micas (including muscovite and sericite) Chlorite (including ripidolite and pyrophyllite Clay minerals (including kaolinite, gibbsite, dickite, natro-alunite	Common
Andalusite Zircon Epidote	Uncommon

Table 5: Chemical Analyses. NUMBER 18A SEAM: HIGHADEN COLLIERY

Sample Number	Bulk Sample Identification	Moisture % A. d. coal	Ash % A. d. coal	% Dry, ash-free basis						% Dry basis				Swelling Number	Selected Sample	
				V.M.	C	H	N	S	O	Total S	Sulph. S	Pyr. S	Org. S		Sub-macrotype	Ash % A. d. coal
4	Duro-clarain	2.1	19.1	32.9	83.8	6.0	1.7	0.8	7.7	0.63	0.07	0.04	0.52	5	Duro-clarain Duro-clarain	17.0 14.8
3	Duro-clarain	-	-	-	-	-	-	-	-	-	-	-	-	-	Duro-clarain Duro-clarain	17.5 17.2
2	Duro-clarain	1.9	13.7	33.7	84.7	5.3	1.6	1.2	7.2	1.02	0.05	0.12	0.85	4½	Duro-clarain	17.8
1	Clarain	-	-	-	-	-	-	-	-	-	-	-	-	-	Clarain	9.4

Table 6: Chemical Analyses. NUMBER 17 SEAM: SHELATAND COLLIERY

Sample Number	Bulk Sample Identification	Moisture % A. d. coal	Ash % A. d. coal	% Dry, ash-free basis						% Dry basis				Swelling Number	Selected Sample	
				V.M.	C	H	N	S	O	Total S	Sulph. S	Pyr. S	Org. S		Sub-macrotype	Ash % A. d. coal
4	"Durain"	1.6	51.3	25.4	84.0	5.4	1.7	1.5	7.4	0.99	-	-	0.99	1½	Durain Durain"	18.0 33.8
3	Duro-clarain	1.7	16.6	33.5	84.1	5.3	1.7	1.1	7.8	0.90	0.03	0.03	0.84	6	Duro-clarain Duro-clarain	9.1 12.7
2	Duro-clarain	-	-	-	-	-	-	-	-	-	-	-	-	-	Duro-clarain	12.8
1	Duro-clarain	2.1	12.5	28.8	84.7	5.4	1.8	0.8	7.3	0.7	0.1	-	0.6	6½	Duro-clarain	11.6

Table 7: Chemical Analyses. KARGALI SEAM: PIPRADIH COLLIERY

Sample Number	Bulk Sample Identification	Moisture % A.D. Coal	Ash % A.D. Coal	% Dry, ash-free basis						% Dry basis				Seam Number	Selected Sample	
				V.M.	C	H	N	S	O	Total S	Sulph. S	Pyr. S	Org. S		Sub-macrotype	Ash % A. d. coal
12	Durain	1.2	22.2	32.1	82.2	5.6	1.7	1.5	9.0	1.15	0.06	0.40	0.69	2½	Vitrain Durain	5.1 17.6
11	Durain	-	-	-	-	-	-	-	-	-	-	-	-	-	Durain "Durain"	12.9 38.2
10	"Durain"	1.0	30.1	28.3	82.3	5.3	1.7	1.3	9.4	0.96	0.08	0.55	0.33	1½	Durain	21.7
9	Durain	-	-	-	-	-	-	-	-	-	-	-	-	-	Durain	25.8
8	Durain	1.0	20.2	29.1	84.1	5.9	1.7	1.4	6.9	1.08	-	0.42	0.66	2½	Durain	19.9
7	"Durain"	1.2	37.7	31.8	86.0	4.3	1.5	1.6	4.6	1.07	0.07	-	1.00	2½	"Durain" "Durain" "Durain"	32.4 34.7 39.3
6	Durain	1.3	16.8	30.3	85.8	5.6	1.7	1.1	5.8	0.95	0.06	0.28	0.61	2½	Durain	20.2
5	Durain	1.4	16.6	29.6	88.4	4.8	1.7	0.7	4.4	0.58	0.01	0.29	0.28	5	Durain Duroclarain	20.2 15.4
4	Durain	1.2	25.9	29.6	83.0	5.3	1.6	0.9	9.2	0.69	-	0.08	0.57	1	Durain	28.8
3	Durain	4.2	9.8	35.3	84.2	5.4	1.5	1.5	7.4	1.28	0.08	0.04	1.16	2	Durain	23.0
2	Durain	1.4	16.6	27.6	86.5	4.8	1.6	1.0	6.1	0.83	0.08	0.04	0.76	1½	Durain	17.9
1	Durain	1.2	22.2	28.6	76.8	4.5	1.5	1.5	15.7	1.18	-	0.07	1.11	2	Durain Durain	16.9 26.4

Composite or rock fragments, largely metamorphic, were not uncommon. The proportions of the sedimentary mineral matter generally increase with those of the organic "inerts" (fusain and micrinite) marking the change of coal type from the relatively minor clarain through duro-clarain to durain (Fig. 11).

As represented by the samples submitted for examination, the coal types duroclarain and durain, characterized by considerable community of character and significant proportions of the sedimentary mineral matter, were dominant in all the seams. Quite conspicuous is the rapid alternation of micro-bands of contrasted coal types which for convenience may be referred to as coal "microtypes." Even in coal blocks that superficially appeared to be of reasonably uniform character (particularly in duroclarains), the microbanding is

commonly well developed. As not only the occurrence and proportions, but also the distribution of the vitrinite, fusinite, micrinite and sedimentary mineral matter in macro- and microtypes is of importance to the utilization properties of the coal, this characteristic was particularly interesting.

Table 8: Chemical Analyses. TOP SEAM: SIRKA COLLIERY

Sample Number	Bulk Sample Identification	Moisture % A. d. coal	Ash % A. d. coal	% Dry, ash-free basis						% Dry basis				Swelling Number	Selected Sample	
				V.M.	C	H	N	S	O	Total S	Sulph. S	Pyr. S	Org. S		Sub-macrotype	Ash % A. d. coal
5	Durain	4.9	15.6	40.0	79.4	5.6	1.6	1.1	12.3	0.90	0.05	0.03	0.82	1½	Durain	10.9
4	Duro-clarain	-	-	-	-	-	-	-	-	-	-	-	-	-	Duro-clarain	13.2
															Duro-clarain	13.5
3	Durain	5.4	9.6	38.6	79.6	5.5	1.6	1.0	12.3	0.89	0.08	0.04	0.77	1½	Vitrain	3.4
															Duro-clarain	12.0
2	Durain	4.6	8.8	34.6	79.8	5.3	1.5	1.0	12.4	0.89	0.09	0.04	0.76	1½	Durain	16.9
1	Duro-clarain	5.1	9.8	37.1	80.2	5.3	1.6	1.3	11.6	1.14	0.11	0.09	0.94	1½	Duro-clarain	10.9

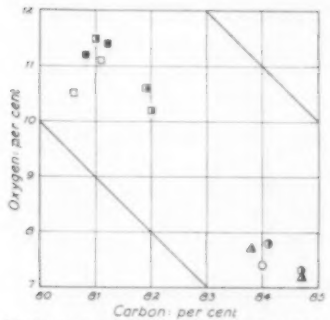
Table 9: Chemical Analyses. BOTTOM SEAM: SIRKA COLLIERY

Sample Number	Bulk Sample Identification	Moisture % A. d. coal	Ash % A. d. coal	% Dry, ash-free basis						% Dry basis				Swelling Number	Selected Sample	
				V.M.	C	H	N	S	O	Total S	Sulph. S	Pyr. S	Org. S		Sub-macrotype	Ash % A. d. coal
4	Durain	-	-	-	-	-	-	-	-	-	-	-	-	-	Durain	12.6
3	Durain	4.2	8.7	33.2	81.7	5.3	1.5	0.8	10.7	0.78	0.04	0.13	0.61	1½	Durain	9.0
2	Duro-clarain	4.1	9.5	35.6	81.5	5.3	1.5	0.9	10.8	0.86	0.12	0.11	0.63	1½	Durain	10.8
															Durain	11.5
		4.0	19.4	40.4	81.1	5.3	1.5	1.4	10.7	1.09	0.09	0.13	0.87	2½		
1	Duro-clarain	4.0	7.5	36.2	81.0	5.0	1.5	1.8	10.7	1.24	0.03	0.20	1.01	1½	Clarain	5.6
															Duro-clarain	9.8
															Durain	10.5

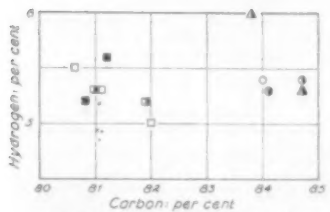
5"

Table 10: Chemical Analyses. ARGADA TOP SEAM: SINKA COLLIERY

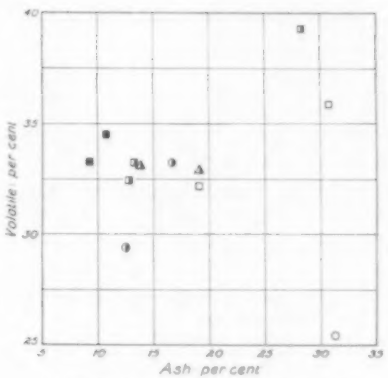
Sample Number	Bulk Sample Identification	Moisture % A.D. Coal	Ash % A.D. coal	% Dry, ash-free basis						% Dry basis				Swelling Number	Selected Sample	
				V.M.	C	H	N	S	O	Total S	Sulph. S	Pyr. S	Org. S		Sub-maceratype	Ash % A.D. coal
13	Durain	4.0	28.1	38.8	80.8	5.3	1.6	2.2	10.1	1.57	0.12	0.24	1.21	1½	Vitrain	3.7
															Durain	13.6
															"Durain"	34.1
12	Durain	3.8	24.3	41.0	81.1	5.3	1.7	1.3	10.1	1.34	0.12	0.24	0.98	1	"Durain"	33.7
															Duro-clarain	20.9
11	Durain	3.5	29.9	44.6	81.3	5.2	1.7	1.3	10.5	0.89	0.18	0.23	0.48	1½	"Durain"	36.5
10	Durain	3.9	12.7	35.8	81.0	5.4	1.6	0.9	11.1	0.78	0.11	0.14	0.53	1	Durain	14.2
															"Durain"	38.7
9	Durain	4.3	9.6	35.7	80.8	5.4	1.5	0.6	11.7	0.57	0.09	0.18	0.30	1½	Durain	9.5
															Durain	11.5
8	Durain	4.0	8.6	35.9	79.9	5.6	1.5	1.1	11.7	1.04	0.08	0.17	0.79	1½	Durain	12.3
7	Durain	4.0	7.9	35.5	82.0	5.2	1.6	1.5	9.7	1.37	0.07	0.09	1.21	1½	Durain	5.9
6	Durain	3.9	14.9	34.8	82.1	5.2	1.6	1.1	10.0	0.97	0.09	0.18	0.70	1½	Durain	13.2
5	"Durain"	-	-	-	-	-	-	-	-	-	-	-	-	-	"Durain"	32.6
4	Durain	3.3	17.3	38.1	82.1	5.2	1.6	1.3	9.8	1.09	0.03	0.31	0.75	1½	Durain	15.8
3	Durain	3.4	28.3	42.2	82.6	5.2	1.6	1.3	9.3	1.10	-	0.28	0.82	1½	Clarain	17.9
															Durain	27.9
2	"Durain"	3.0	42.5	45.6	80.3	5.6	1.5	1.9	10.7	1.07	0.05	0.31	0.71	1½	"Durain"	45.7
1	Durain	3.7	15.1	39.4	80.1	5.5	1.6	1.7	11.1	1.04	-	0.35	0.69	1½	Durain	28.7



(a) Carbon-oxygen variation according to coal type, all seams



(b) Carbon-hydrogen variation according to coal type, all seams

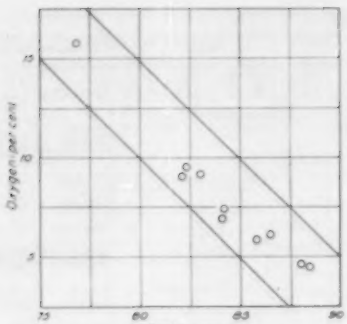


(c) Volatile ash variation according to coal type, all seams

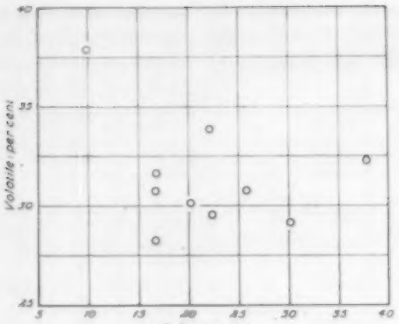
LEGEND

Seam	Clarain	Durclarain	Durain
Number 17	●	◑	○
Number 16A	▲	◭	△
Number 16	■	◨	□

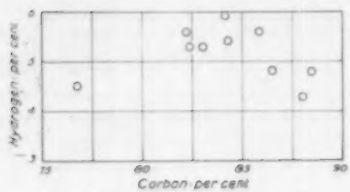
Figure 4. VARIATION IN NUMBERS 16, 16A AND 17 SEAMS, DIGWADIH AND BHELATAND COLLIERIES, JHARIA COALFIELD



(a) Carbon - oxygen variation



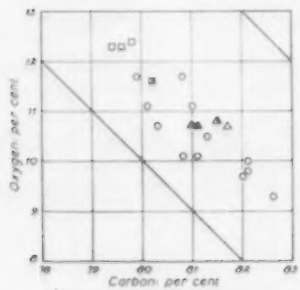
(c) Volatile - ash variation



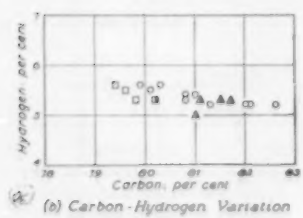
(b) Carbon - hydrogen variation

LEGEND
○ Durain

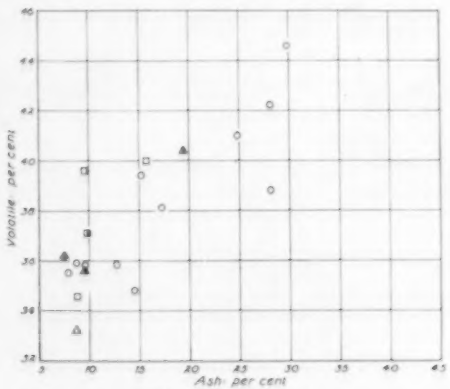
Figure 5. VARIATION IN KARGALI SEAM, PIPRADIH COLLIERY, BOKARO COALFIELD



(a) Carbon - Oxygen Variation



(b) Carbon - Hydrogen Variation



(c) Volatile - Ash Variation

LEGEND

Seam	Clarain	Duroclarain	Durain
Sirka Top Seam	■	▣	□
Sirka Bottom Seam	▲	▲	△
Argada Top Seam	●	◕	○

Figure 6. VARIATION IN ARGADA TOP SEAM SIRKA BOTTOM AND SIRKA TOP SEAMS - SIRKA COLLIERY, SOUTH KARANPURA COALFIELD

So as to avoid needless repetition, the salient and common features of the various coal types in the different seams are described generally; particular description is confined to significant characteristics. Although the principal coal types are described separately, it must be emphasized that they are intimately associated and every possible gradation and intermediate condition occurs commonly.

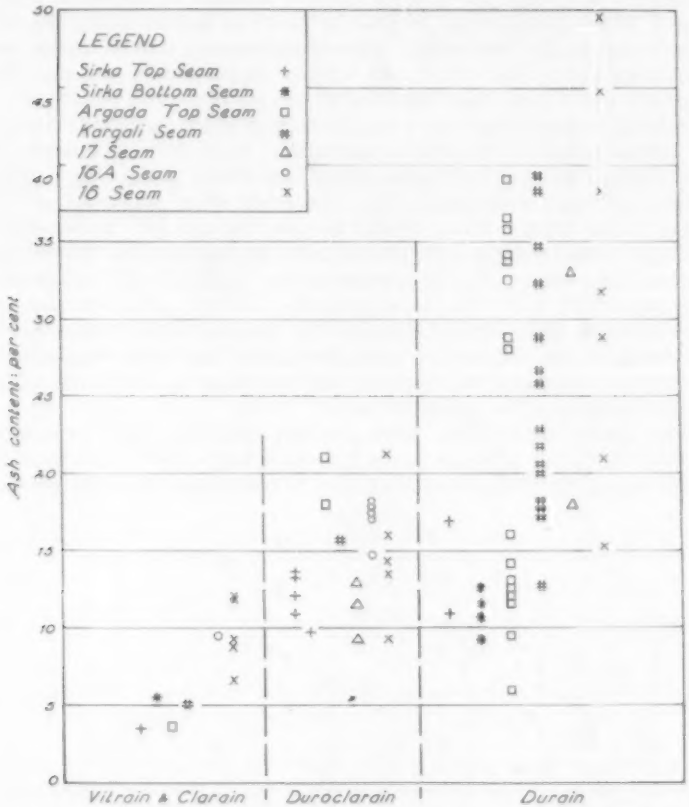


Figure 7. ASH DISTRIBUTION BY SEAM AND MACROTYPE

General Petrology of the Coal Types

Clarain (Plates 1a, 1b, 2a, 2b and 2c).—In the representative samples of the Damodar Valley seams submitted for investigation, clarain did not appear prominently, in this respect being in marked contrast with normal seams of Carboniferous age.

The dominant constituent vitrain or vitrinite (anthraxylon) derived from

fragments of wood (mostly gymnospermous) and bark, is generally in a state of fine division (Pl. 1a). In thickness the sheets average less than 0.2 mm (range of mean thickness 0.046 to 0.188 mm) and although individuals were recorded up to 7 mm, they seldom exceeded 2.0 mm (Table 1, Pl. 2b). Even in the finest states of disintegration the boundaries of the vitrinite fragments appeared clearly defined. The few macroscopic vitrain bands that could be extracted for individual examination had ash contents of the order of 3 to 5 percent, largely representing original carbonate as well as minor clay mineral occurring in fine microscopic joints; micro-concretions of pyrite were comparatively rare. The vitrain and vitrinite proportions in the macrotype vary greatly and in some cases exceeded 90 percent of the coal substance.

Lenticular bodies of fusain are quite common in which the cell cavities commonly contain either clay material or carbonate. Many individual sheets representing former wood or bark tissues exhibit transitions between the condition of vitrain and fusain (vitrifusain: 14). Generally entire fragments are preserved in this condition. Finely divided fusinite, micrinite and "intermediates" were disseminated throughout the clarain mass or occur in minor relative concentrations along the bedding planes, commonly associated with sedimentary mineral matter (Pl. 1, 2). Increased proportions of micrinite, generally associated with more finely divided vitrinite and increased sedimentary mineral matter, mark the development of micro-duroclarain and micro-durain bands. In the clarains examined, the range of mean thickness for the inert constituents varies between 0.008 and 0.049 mm.

Spores, cuticles and "resins" were generally present in minor proportions (less than 1%) which however rarely became of local importance (Table 1).

Quite commonly, alternations of clarains of contrasted character, generally

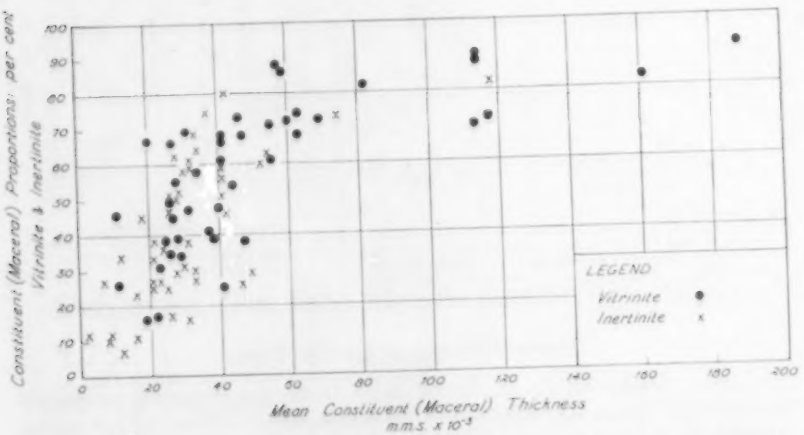


Figure 8. RELATION BETWEEN CONSTITUENT (MACERAL) PROPORTIONS AND MEAN DIMENSIONS

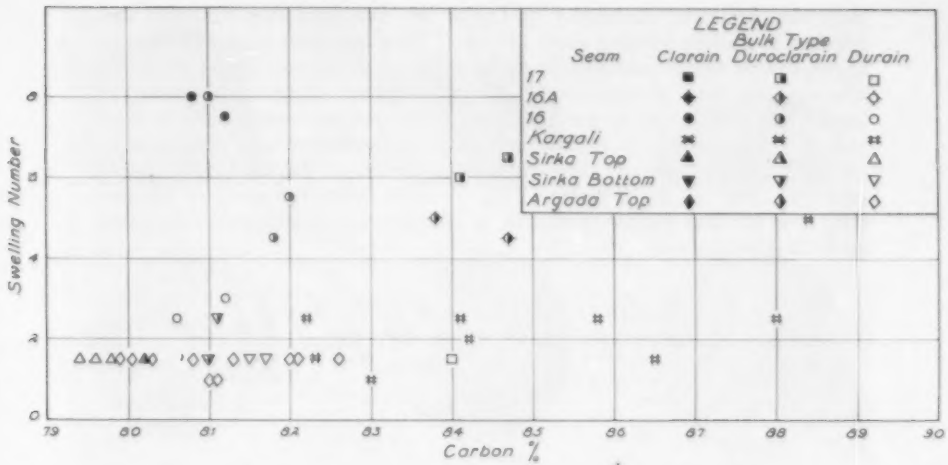


Figure 9. BULK COAL TYPE AND CARBON CONTENT RELATED TO FREE SWELLING NUMBER; ALL SEAMS

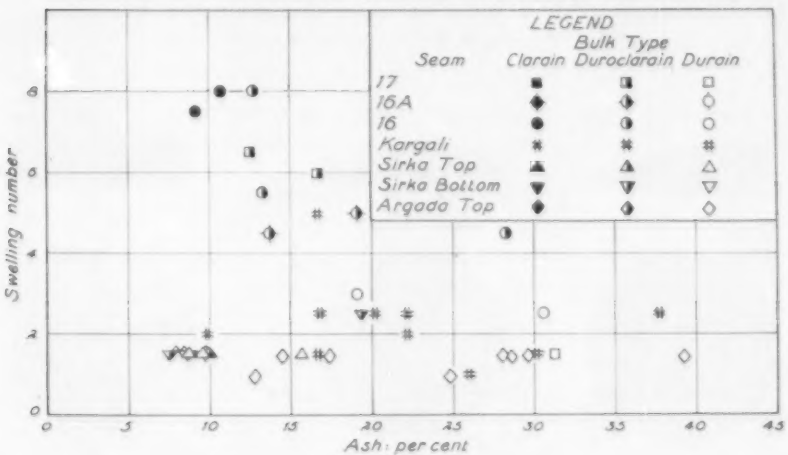


Figure 10. BULK COAL TYPE AND ASH CONTENT RELATED TO FREE SWELLING NUMBER; ALL SEAMS

most evident in the mean grain size and distribution of the constituents, emphasizes the banding of the macrotype; such alternations are quite clearly demarcated.

Sedimentary mineral matter is rarely conspicuous microscopically in the clarains except at few and restricted horizons (Pl. 2a, 2b). Individual mineral

fragments are quite common (Pl. 1a) as are also local fine concentrations confined to a single bedding plane (Pl. 2c). In a few cases, marked lenticular aggregates of "clay" minerals occur in zones up to 80 microns in thickness. The size–frequency distribution of the visible clastic mineral grains is represented in Table 3. Micro-concretions of pyrite and carbonate minerals (calcite and siderite) are fairly common, generally restricted to a single clarain or even individual vitrain sheet. The ash content of the clarains examined generally range up to 12 percent (Fig. 7) with an overall mean of 8.8 percent; one unusual sample consisting of vitrinite and clastic mineral ranged up to 35.3 percent ash.

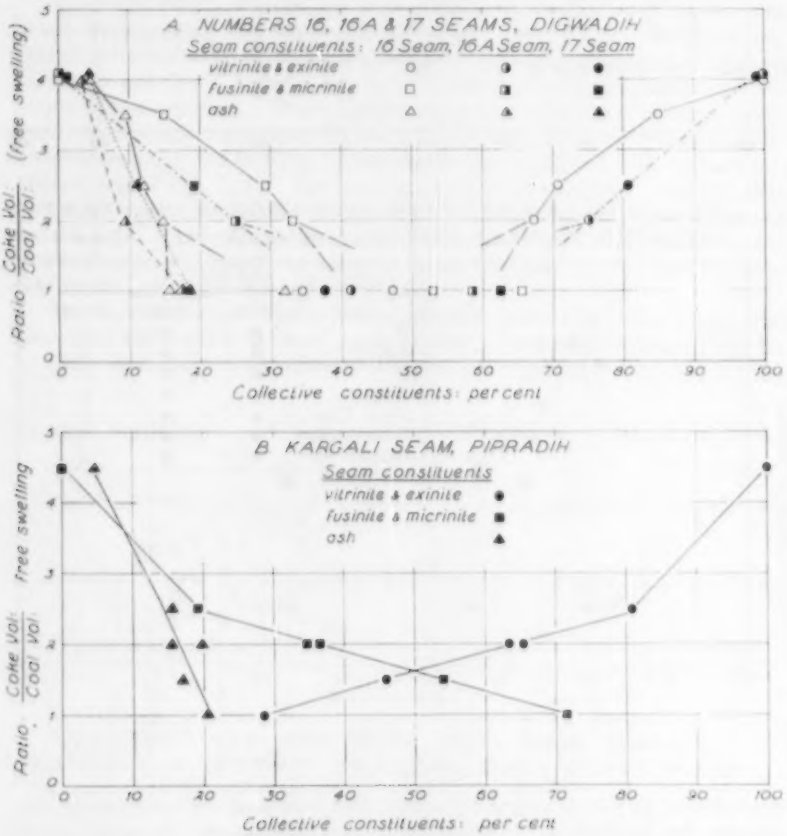

A NUMBERS 16, 16A & 17 SEAMS, DIGWADIH
Seam constituents: 16 Seam, 16A Seam, 17 Seam
vitrinite & exinite
fusinite & micrinite
ash
Ratio Coke Vol / Coal Vol (free swelling)
Collective constituents: per cent
B KARGALI SEAM, PIPRADIH
Seam constituents
vitrinite & exinite
fusinite & micrinite
ash
Ratio Coke Vol / Coal Vol free swelling
Collective constituents: per cent

Figure II. COLLECTIVE MACERAL CONSTITUTION AND ASH CONTENT OF SELECTED MACROTYPE SAMPLES RELATED TO GENERAL CHARACTER OF COKE PRODUCED (FREE SWELLING)

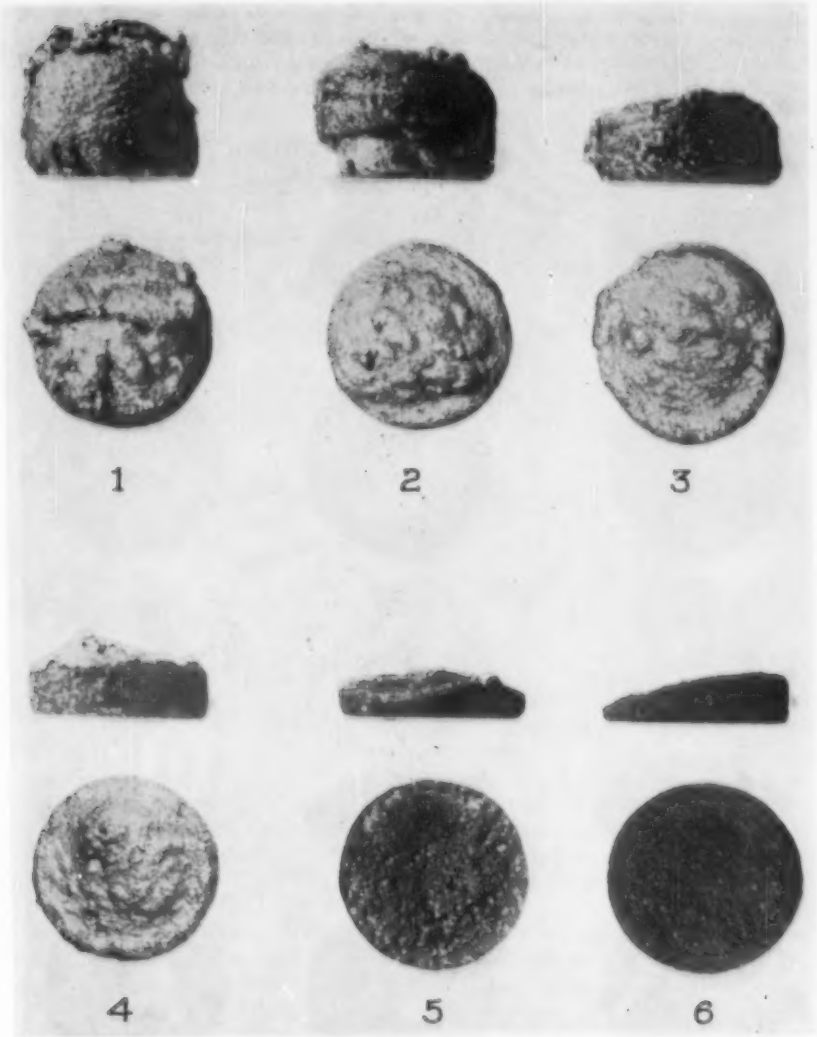


PLATE 5. Variation in cokes produced from selected macrotype samples of the Number 16 seam, Digwadih Colliery, Jharia Coalfield. (1) Vitrain; (2) Clarain A; (3) Clarain B; (4) Duroclarain; (5) Durain A; (6) "Durain" B.

Although the clarains are generally of relatively low ash content and appear visually to be quite conspicuously low in content of sedimentary mineral matter, block ashing revealed that a considerable proportion of the mineral occurred as very finely divided, widely disseminated material (Pl. 3b). The distribution is

such as to indicate the presence not only of plant ash occurring throughout each plant fragment, but also of very minutely divided clay mineral occurring interstitially, possibly as extremely fine "films" on the surfaces of the macerals. The results of quantitative block ashing studies, coupled with the relatively

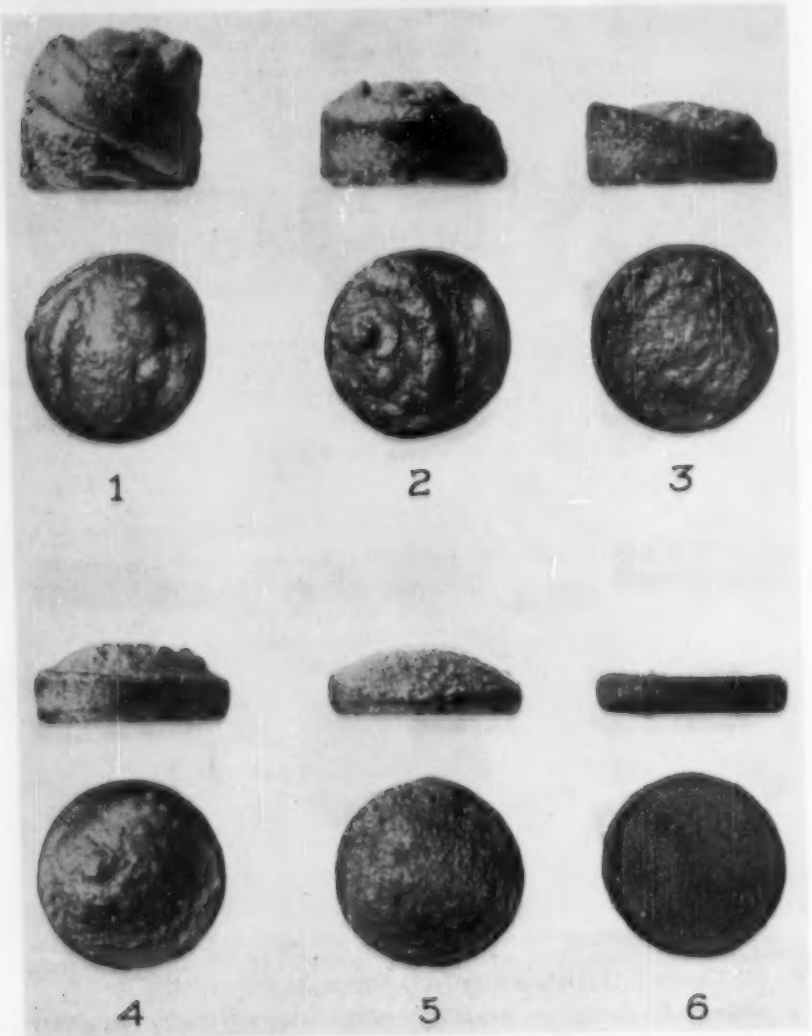


PLATE 6. Variation in cokes produced from selected macrotype samples of the Kargali seam, Piphadih Colliery, Bokaro Coalfield. (1) Vitrain; (2) Clarain; (3) Duroclarain A; (4) Duroclarain B; (5) Durain A; (6) Durain B.

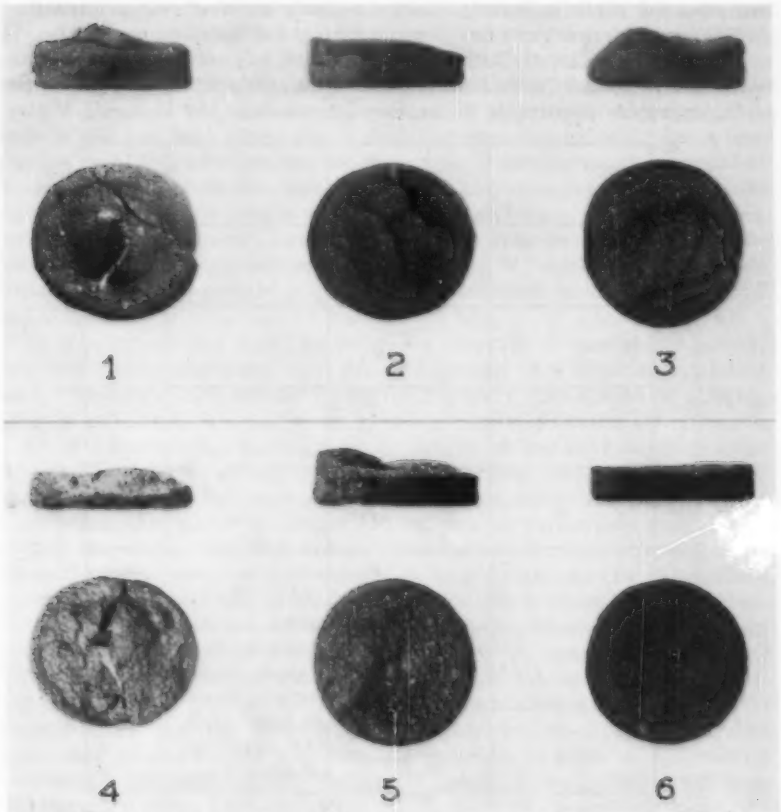


PLATE 7. Variation in cokes produced from selected macrotype samples of the Argada and Sirka Top seams, Sirka Colliery, Karanpura Coalfield. (1) Duroclarain, Sirka; (2) Duroclarain, Sirka; (3) Durain, Sirka; (4) Clarain, Argada; (5) Duroclarain, Argada; (6) Durain, Argada.

inconspicuous mineral proportions revealed microscopically in thin sections and polished blocks, indicates that a considerable proportion of the total mineral occurs in this extremely finely divided state and is consequently quite impossible to reduce effectively by any normal means; extreme measures of ultra-fine grinding could possibly release a large part of this mineral but would be economically quite impracticable. Even the more coarse, "visible" sedimentary mineral would be extremely difficult to reduce appreciably except where present in thicker bands or lenticles that might be released, completely or in part, by appropriate breakage.

As compared with clarains of the Carboniferous bituminous coals of corresponding petrological constitution, those of the Damodar Valley tend to exhibit a diminished lustre. This is most probably due to the generally fine state of

division of the vitrain and vitrinite, the commonly rapid alternation of micro-banding, and the remarkably fine dissemination of the "clay" mineral.

Durain (Plates 1e, 1f, 2d and 2e).—Of relatively minor proportions as represented in normal Carboniferous seams of the northern hemisphere, durain is of considerable importance in the Permian seams of the Damodar Valley

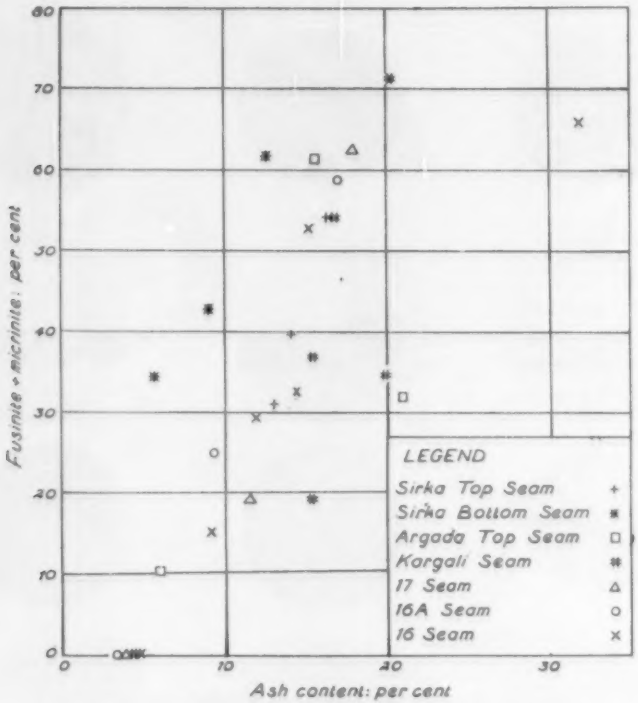


Figure 12. ASH CONTENT IN RELATION TO PROPORTIONS OF FUSINITE AND MICRINITE

coalfields. Many of the samples studied are either entirely of this coal type or consist of intimate micro-alternations of clarain and durain, to form macro-duroclarains.

Vitrinite in relatively subordinate proportions (16 percent to 48 percent) occurs generally in finely divided, irregular sheets and fragments of which the mean thickness ranged between 0.011 and 0.047 mm (Table 1; Pl. 2e, 2f). Indeed, a considerable part of this material appears to have been so finely disintegrated as to be represented by fragments of individual cell wall thickness. Such structure as remained in the vitrinite sheets indicate wood and bark tissues as the source materials, identical in character with those preserved in the clarains.

Fusinite occurs in coarse and fine lenticular bodies in which the few open cell cavities are commonly occupied by carbonate or clay mineral. More generally the lenticles are highly compacted with the almost complete elimination of the cell cavities. Smaller masses of fusinite are particularly common.

In addition to the characteristic modes of preservation represented in vitrinite and fusinite, a proportion of the plant-fragments exhibit either a progressive transition between the two extremes or an intermediate condition. Macerals which in their structure and physical properties resemble sclerotinite occur sporadically. Micrinite and similar finely divided, granular materials (commonly in aggregates) form with fusain and fusinite a considerable proportion of the coal type, ranging between 50 and 82 percent. Mean particle thickness of these macerals in the samples examined varies between 0.026 and 0.118 mm.

Spores, cuticles and resin-like bodies are generally present in low proportions but locally constituted as much as 7 percent of a single micro-durain band. Bedding in the durains varies from a fairly well defined to a highly irregular condition.

In both macroscopic and microscopic durains, sedimentary mineral matter is generally evident, although a few of those examined are unexpectedly low in ash. The visible clastic grains occur either more or less homogeneously disseminated throughout the durain (Pl. 1a, 2d), or particularly concentrated in both macroscopic and microscopic bands which, through progressive increase of mineral, pass into carbonaceous shales and siltstones (Pl. 2e). There is a general but quite well defined tendency for clastic mineral content to increase with the proportions of fusinite and micrinite. In the group of durains and carbonaceous sediments studied, the ash content ranges between 6 and 49.5 percent, with an overall mean of 20.7 percent. Ash content ranges, distribution and broad relation to fusinite–micrinite content are represented in Figures 7, 11, and 12. Macroscopically, apart from a slightly diminished lustre and increased density it was not generally possible to discriminate between the high and low ash "durains." Indeed, in many moderately high and low ash durains, the luster of the coal is commonly deceptively high. As modern practice has demonstrated that solid "fuels" with more than 40 percent ash may in some circumstances be used economically for certain industrial purposes these high-ash bands have been included as "durains" despite former reluctance to regard as coal any carbonaceous deposit with more than 30 percent ash.

The macrotype durains in some cases represent a more or less homogeneous association of the various macerals in reasonably consistent proportions. Commonly they consist of rapid, micro-banded alternations of slightly contrasted but clearly differentiated micro-durains in which either the proportions or mean dimensions of both macerals and minerals vary. A further source of micro-banding is the presence of thin, subordinate micro-clarain or micro-duroclarain layers in the overall macrotypes. The micrometric analyses of Table 1 indicate the fine scale on which the microtype banding may be developed.

In thin and polished microsections it is evident that increased contents of

ash in both macro- and microtypes are generally the result of greater proportions and some change in the character of the sedimentary mineral matter. In the higher ash durains the range of particle size generally increases, although many of the carbonaceous rock bands consist largely of silt and clay-grade material.

Ash skeletographs commonly exhibited a pronounced "banding" due to the somewhat contrasted proportions and characteristics of the sedimentary minerals in the various layers (Pl. 3, 4). In the low-ash durains it is quite evident that a considerable proportion of the mineral matter occurs as extremely finely divided material, more or less uniformly dispersed, interstitial to the macerals and therefore extremely difficult to separate.

The constitution and physical characteristics of these very important seam components, the durains, demonstrated the inherent and serious difficulties attending efforts to reduce substantially their ash content. The character, distribution, size and relations of both microtype and macrotype bands have an extremely important bearing upon the cleaning potential of these coals, which clearly is quite differen from that of normal Carboniferous seams of the northern hemisphere.

Duroclarains (Plates 1c and 1d).—Intermediate in their constituent proportions between clarain and durain, coals of a type that macroscopically would be identified as duroclarain form an important proportion of the majority of the Damodar Valley coals examined. Microscopically, a considerable proportion of this type of coal consists of rapid alternations of thin layers of clarain and durain, each exhibiting "in miniature" the essential characteristics of their particular coal type. Their intimate association precludes any likely economic possibility of mechanical separation.

The microscopically more homogeneous duroclarains vary in character according to the degree of disintegration represented in the macerals. Very fine sheets of vitrinite commonly alternate in a more or less regular fashion with layers in which fusinite, granular micrinite and clastic mineral are conspicuous (Pl. 1c). Alternatively, rather more massive and generally highly irregular vitrinite masses are associated with larger fusain and fusinite bodies together with micrinite (Pl. 1d). Variations in and between these two conditions are common.

In the duroclarains subjected to micrometric analysis, the mean thickness of the vitrinite sheets ranges between 0.020 mm and 0.063 mm; for the "inert" constituents the variation is between 0.007 mm and 0.092 mm. Spore material and microscopically visible clastic mineral matter are generally low. In selected samples the ash of the duroclarains varied between 9 and 23 percent with a mean content of 14.3 percent.

The widespread distribution of fine sedimentary mineral and its intimate, interstitial association with the organic constituents of the coal are apparent in the ash skeletographs (Pl. 4a). Adjacent bands, both macro- and microscopic, are generally in strong contrast as regards proportions and character of included mineral matter (Pl. 3b, 4a). Micro-concretions of pyrite and siderite occur in relatively few and commonly well defined layers.

In general, the various coal types exhibit a systematic progressive variation

in constituent proportions and sizes. From durain, through duroclarain to clarain the increase in vitrinite content is generally accompanied by an increase in mean particle size much more pronounced when the proportions of this constituent exceeded 70 percent (Fig. 8). For the inert constituents the relationship between maceral size and range is less emphatic (Fig. 8). In general there is an increase in total and microscopically identifiable mineral matter in the duroclarains and durains. The generally sympathetic variation in content of "inerts" and mineral matter is evident in Figure 12.

Characteristics of Seam Samples

Jharia Coalfield, Seams 16 and 16A of Digwadih; Seam 17 of Bhelatand.—With few exceptions, duroclarain is the dominant macrotype in the representative samples of these three seams (Fig. 1; Tables 4, 5, 6). In many of them macrotype banding was evident, and practically all exhibit rapid variation of coal type on a microscopic scale.

Each of the chemical analyses (Tables 4, 5, 6) is representative of the entire sample submitted but wherever practicable coal type specimens were extracted from the blocks for more specific examination, particularly as regards micropetrological constitution, ash and coking characteristics.

Both type and rank variation, individually or together, may normally be responsible for variations in the chemical characteristics of the solid fuels. By correlating the results of both micro-petrological and chemical analyses of selected samples, more precise information is obtained as to the character of the coal and ambiguity of interpretation is reduced.

On the curve of carbon–oxygen variation, the macrotype samples of the 16 seam form a separate group of rather lower total carbon than those of either the 16A or 17 seams; the latter are quite closely associated (Fig. 4a). Greatest variation in proportions of carbon and oxygen are exhibited by the duroclarains; there appears to be little significance in the hydrogen–coal type relationship (Fig. 4b). From the clarains through the duroclarains into the medium ash durains (less than 20%) there is a general increase in ash content with a slight decrease in volatile yield (Fig. 4c), probably due to the increase in the proportions of "inertinites." The very high volatile–high ash association exhibited by two samples is due to the presence of carbonate micro-concretions.

To assess the range of potential variation in coking characteristics inherent in each seam as a result of coal type variation and to obtain information as to the possible effects of different degrees of preparation, individual macrotype specimens were extracted from the representative samples for micrometric analysis and used to produce crucible cokes. Each of the 16, 16A, and 17 seams exhibits a closely comparable range of variation in the character of the coke yielded by the various coal types. In each case, from the highly swollen and relatively weak cokes of the vitrinites and clarains, the series passes progressively into the stronger, less swollen cokes of the duroclarains and thence to the weaker, feebly or non-coherent residues of the durains (Table 2; Pl. 5).

In Figure 11A the volumetric increase on coking the macrotype specimens

of each seam is related to the micrometric proportions of the actively coking constituents (dominant vitrinite and subordinate exinite) and the "inert" components (fusinite and micrinite) as well as to the ash content. The relationship varies in degree with each seam but the trends are definite and comparable. With decrease in the vitrinite content of the coal, the cokes become much less swollen and it would appear that for these seams little or no effective volume change occurred during coking when there was approximately 60 percent or less of this constituent present in the original charge. Coke formed from coal (of these particular seams) with 60 percent vitrinite is relatively strong, coherent and lustrous, but these properties deteriorate quite rapidly with further decrease in the proportions of this constituent.

Other studies recently completed (24; 25) have demonstrated the potential importance of the inert seam constituents (fusinite, micrinite and mineral) as factors affecting the coking properties of high volatile bituminous coals. In the present instance it was not possible to evaluate these factors individually but the proportions of both organic and mineral inerts increased progressively in those coals that yielded successively less swollen cokes (Fig. 11a). The general and evident sympathetic variation in proportions of ash with those of fusinite and micrinite is also of considerable potential significance in connection with preparation to secure optimum coke quality.

Bokaro Coalfield, Kargali Seam, Pipradih Colliery.—Although macrobands of all normal coal types did occur in the available seam samples, durain was dominant in every representative specimen of the Kargali seam available for study. One three-foot band of "coke" and stone (presumably intrusive igneous rock) and a lower five-inch band of coke did not appear to be associated with any appreciable deterioration in other samples from positions either above or below the immediately affected section of the seam (Figs. 2, 5; Table 7). The chemical analyses (Table 7) are each representative of the entire sample submitted; wherever practicable, macrotype specimens were extracted for more specific study including determination of petrological constitution, ash content and character of the free swelling crucible coke.

The range of variation in the carbon and oxygen content of the samples is considerable (Fig. 5). This range is extended particularly by the relatively low carbon and hydrogen contents of the specimen representing the lowest section of the seam which, however, is not remarkable in any other way. A tendency towards a decrease in volatile yield with increase in ash content is in accordance with the generally observed association of higher proportions of inertinite with increased mineral matter in the durains (Fig. 5c).

The crucible cokes produced from selected macrotype specimens (Pl: 6; Table 2) exhibited a range of variation comparable with those of the Jharia seams previously discussed. The coarsely cellular, highly swollen, tender cokes of the vitrinite are exceeded in strength by the more compact, fine-textured products of the clarains and duroclarains. Durains with proportions of fine vitrinite not much inferior to those of the duroclarains also yield compact, strong cokes, but with greater contents of the organic and inorganic "inerts" (fusinite, micrinite and mineral matter) they became much less coherent and diminished in lustre (Table 2; Pl. 6). The general relationship

between swelling characteristics and the volumetric proportions of the seam constituents (vitrinite and exinite: fusinite and micrinite) is quite evident (Fig. 11b). Although much more detailed quantitative study would be necessary to evaluate critically their relative coking characteristics, it appears possible that the coal types of the Kargali seam of Pipradih are superior in this respect to those of the 16, 16A and 17 seams of the Jharia field previously examined.

South Karanpura Coalfield, Argada Top, Sirka Bottom and Sirka Top Seams, Sirka Colliery.—All representative samples of the thick Argada Top seam were dominantly of durain; the specimens of the two Sirka seams could be generally referred to either duroclarain or durain (Fig. 3). As in the seams of Jharia and Bokaro, with care the common macrotypes durain, duroclarain, and clarain could be extracted from a proportion of the samples submitted.

Although the chemical variations in the three seams are represented together in Figure 6, the range exhibited is quite restricted. Total carbon varies between 79 and 83 percent with the durains of the highest seam occurring in the low carbon region of the curve; the durains of the lowest seam (Argada Top) are distributed almost throughout the entire range. The variation in hydrogen content is restricted and exhibits a tendency to decrease in the higher carbon samples. The volatile yield increases generally with ash content and is almost entirely a response to the common and quite widespread development of micro-concretions of carbonate minerals in the Argada Top seam (Fig. 6c).

The cokes produced from the various selected macrotype specimens of the representative samples were very restricted in their physical properties. Clarains generally yielded slightly shrunken, coherent cokes of moderate to slight strength and luster (Pl. 7). The products of duroclarains and durains are feebly coherent to friable in character and not swollen. In their coking properties these seams of the Sirka area of South Kuranpura are quite different from those of Jharia and Bokaro previously examined.

PREPARATION AND COKING POTENTIAL OF THE SEAMS EXAMINED

The samples available from each seam were too few and restricted in character to permit truly critical and reliable assessment of the cleaning and utilization potential of each coal bed. On the limited basis of the group studies, however, certain general deductions appear reasonable even though subject to qualification in the light of more exhaustive examination and experience.

As revealed by microscopic examination and the character of the skeletographs, a considerable proportion of the inorganic matter normally present occurs as very finely divided sedimentary mineral particles interstitial to the coal constituents or macerals. Such clastic mineral matter occurs dispersed in even the relatively low-ash bright bands or clarains in all of the seam samples examined; in these the average total ash amounted to 8.8 percent. Local but very minor concentrations of clastic mineral occur quite commonly along individual bedding planes of the clarains but could be reduced only by extreme methods of breakage and separation.

Changes of coal type from clarain to duroclarain and durain are generally accompanied by evidently increased proportions of sedimentary mineral matter and overall ash content. The higher proportions in the duroclarains commonly occur as general increases in the disseminated clastic mineral througnout the coal type with some local concentrations in definite microbands; the mean ash content of the duroclarains studied is 14.3 percent. In durains, in addition to an apparent general "overall" increase in the disseminated clastic mineral, concentrations on a microscopic or larger scale are common, particularly in samples of which the ash content exceeds 25 or 30 percent; the mean ash content of all durains studied amounts to 20.7 percent.

From a consideration of the micropetrology, distribution and relative proportions of the coal types in the seams, it is evident that, apart from the elimination of the obvious stone layers and partings, the cleaning potential of these coals is largely conditioned by the possibilities of reducing effectively the proportions of high-ash durain and carbonaceous shale-silt bands that they commonly contain.

The clarains appear to be of minor significance in this respect, as they form a relatively small proportion of the seams. The durains vary greatly in their constitution, high mineral content and scale of banding from a condition closely resembling the duroclarains to one in which they approach normal stone bands. The duroclarains, although also rather variable in character, are generally relatively homogeneous or characterized by micro-banding on such a fine scale as would not readily permit economic separation of their common, micro-durain components. It would thus appear most probable that truly efficient preparation and cleaning should yield an optimum product in which the ash content, although subject to variations dependent upon individual seam characteristics, should approximate that of the average duroclarain, namely 14.3 percent.

These results have been consistently achieved and bettered by the Tata Corporation at their West Bokaro and Jamedaba collieries where the Chance process has been in successful operation for more than three years (3).

Opinions differ widely both in producer and consumer groups as to the essential or optimum qualities required in a coke. Each of the seams examined in this study exhibits potentially appreciable and in places considerable variation in the character of the coke produced from the various coal types present. This variation in coke character has been related to the proportions and distribution of the coking and non-coking constituents (i.e., to the coal types) (Fig. 11) a relationship which is particularly evident in the case of the 16, 16A, 17 and Kargali seams.

The close and sympathetic variation in the proportions of inertinite and mineral matter generally exhibited in the coal types, indicates that an efficient cleaning operation would not only reduce the mineral content but also that of inertinite; the relative proportions of vitrinite would be increased in the clean fractions. This possibility of modifying the coking characteristics of the seam by varying the proportions of the constituents present in the oven charge as a result of controlled preparation, is of considerable and general economic importance.

The overall relation of swelling characteristic to coal type, carbon, and ash content for all seams is broadly summarized in Figures 9 and 10. It is apparent that in general the durains are but feebly swelling throughout the carbon range represented (Fig. 9); the swelling characteristics of clarains and duroclarains tend to decline as either total carbon or ash content increases.

CONCLUSION

From these studies it is evident that, despite their difficult character, a modest but highly acceptable reduction of the amount of mineral matter in these coals could be achieved by quite normal methods. The possibility of cleaning fine coal from these seams should be thoroughly explored. Potentially, the coking characteristics of the seams, particularly of the 16, 16A, 17, and Kargali seams, could be profoundly affected by the degree and method of preparation. Due to their intimate and sympathetic association in these seams, significant reduction of mineral matter also entails a reduction in the content of fusinite and micrinite; these constituents influence not only the swelling characteristics of the coal but also the strength of the coke produced. When intended for the production of metallurgical coke, preparation of these seams must be considered not only in connection with the expected benefits of ash reduction but also in relation to control of swelling and swelling pressures during coking, and the production of coke with optimum mechanical properties.

Potential benefits which may be expected from a detailed quantitative study of the variation of coking characteristics of these seams as a result of petrological control in preparation are very considerable and offer an important field for future study.

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SYDNEY, AUSTRALIA,
March 20, 1958

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SULFIDE SOLUBILITY IN AQUEOUS SOLUTIONS

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ABSTRACT

The values for sulfide solubilities in aqueous solutions which are currently available in the geological literature need extensive revision as the result of redeterminations of basic thermodynamic data. New solubility data for nine of the common sulfides are presented. Calculations have been made for temperatures of 25°, 100°, 200°, 400°, and 600° centigrade, at pH values of 3, 7, and 11. The current opinion that the simple solubilities of the sulfides cannot alone account for their transport in ore fluids is not challenged.

INTRODUCTION

RECENT discussions of the mechanisms of transport of the ore metals show that this remains one of the foremost problems facing the economic geologist. There is no need to review here the many mechanisms that have been suggested, but from the first the solubility of the sulfides in aqueous solutions has received widespread attention. It is not possible to calculate what the solubility of the sulfides in a true ore solution should be because of limitations in our present knowledge. We know neither the composition of an "average" ore-bearing fluid, nor the type of complex ions that the sulfides can form or the extent to which they would form them.

It is possible however to make theoretical calculations of sulfide solubilities in simple aqueous solutions. Such calculations, if used with discretion, can give the geologist an idea of the role that sulfide solubilities might play in the problem of ore transport. Verhoogen (17) made such calculations for several of the sulfides in pure water (pH = 7) using the thermochemical data available in 1938. Calculations based on Verhoogen's work, but using various fixed values for total sulfur and a range of values for pH, were made for copper by Garrels (5) in 1944.

Such calculations of sulfide solubility are based on thermodynamic data for each of the ions and compounds considered. These data are subject to revision as more precise measurements are made and some of the data used by Verhoogen have since been modified considerably. Perhaps the most significant revision concerns the reaction

$$HS^- = H^+ + S^{--}.$$

This reaction controls the S^{--} ion concentration, which is of prime importance in the calculation of sulfide solubilities. Verhoogen's value for the ΔH of this reaction was + 3,869 cal/mole, as compared with the now accepted value of + 11,900 cal/mole. Other thermodynamic data have also been significantly, though less drastically, revised.

As the works of Garrels and Verhoogen are still referred to (3), it seems worthwhile to note that these errors exist in their work, and to present solubility data based on the most recent thermodynamic measurements. The solubilities presented differ considerably from those given by Verhoogen, the revisions for individual sulfides following no set pattern. ZnS and PbS are found to have a lesser change of solubility with temperature than Verhoogen had calculated, whereas Ag_2S, Cu_2S, CuS, and HgS all show greater changes. At elevated temperatures (200–400° C), ZnS is much less soluble, PbS significantly less soluble, and Ag_2S more soluble than reported, while the solubilities calculated for Cu_2S, CuS, and HgS differ only slightly from Verhoogen's values. The new data do not alter the conclusion that we must look beyond simple solubilities to understand the transport of ore metals.

TABLE 1

THERMODYNAMIC DATA

Formula	ΔH° kcal/mole	S cal/deg/mole	Formula	ΔH° kcal/mole	S cal/deg/mole
H_2S	− 9.40	29.20	Fe^{++}	−21.00	−27.10
HS^-	− 4.10**	15.00**	FeS_a	−22.72	16.10
S^{--}	7.80**	− 4.60**	Hg^{++}	41.56	− 5.40
Ag^+	25.31	17.67	$HgS_{(r)}$	−13.90	19.50*
Ag_2S_a	− 7.60	34.80	Mn^{++}	−52.30*	−20.00
Cd^{++}	−17.30	−14.60	MnS	−49.00*	18.70
CdS	−34.50	16.50*	Pb^{++}	0.50*	5.10
Cu^+	12.40	− 6.30	PbS	−22.54	21.80
Cu^{++}	15.39	−23.60	Zn^{++}	−36.43	−25.45
CuS	−12.10*	15.90	$ZnS_{(sph.)}$	−48.20*	13.80
Cu_2S	−19.60*	28.50*			

* From Kubaschewski and Evans.
** From Kury, Zielen, and Latimer.
All other data from Latimer.

METHOD OF CALCULATION

The method for calculating the solubilities of the metal sulfides is presented in standard physical chemistry texts and in Verhoogen's original article. Therefore, only the outline of the method will be repeated here and an error in Verhoogen's presentation, which has apparently gone uncorrected, will be noted.

All of the calculations are based on the ΔH and S values given in Table 1. The familiar formula

$$\Delta F = \Delta H - T\Delta S \qquad (1)$$

enables one to calculate the free energy change for each reaction at the chosen temperatures (T in ° K). Such calculations involve the assumption that ΔS and ΔH for the ionization reactions do not change with temperature. More exact calculations of ΔF are not possible because data are not available for the metal ions for the change of ΔH and S with temperature. The use of

the approximate formula is justified in that orders of magnitude are sought in the solubility values and a simplified system has been assumed.

The formula

$$\Delta F = - RT \ln K \tag{2}$$

enables the ΔF values obtained from equation (1) to be converted into values for the solubility product, K, of the sulfide, which are given in column 2 of Table 2.

The solubilities of the sulfides of the divalent metals can be calculated at a given temperature and pH value from the equation

$$(M^{++}) = \sqrt{KX},$$

where K is the solubility product of the sulfide and

$$X = 1 + \frac{(H^+)}{K_2} + \frac{(H^+)^2}{K_1 K_2}.$$

K_1 and K_2 are in this case the two dissociation constants of hydrogen sulfide:

$$K_1 = \frac{(H^+)(HS^-)}{H_2S}$$

and

$$K_2 = \frac{(H^+)(S^{--})}{HS^-}.$$

For the sulfides of the monovalent metals the solubility is calculated from a similar formula,

$$(M^+) = \sqrt[3]{2KX}.$$

The formula derived by Verhoogen,

$$(M^+) = \sqrt[3]{\frac{KX}{2}},$$

is incorrect.

The third, fourth, and fifth columns of Table 2 contain the solubilities of the sulfides calculated in the manner described. It should be noted that these calculations are subject to the experimental uncertainty of the thermodynamic measurements. The probable error of the ΔH values is $\pm$ 0.5 kcal/mole and that of the S values $\pm$ 0.5 cal/deg/mole. These uncertainties will not change the order of magnitude of the calculated solubilities.

The solubilities calculated for 400° and 600° C involve considerable extrapolation of the basic data and are less reliable than those calculated for lower temperatures. At temperatures near the critical temperature of water (374° C) the ore fluids may pass into the supercritical state. The calculations for temperatures that may exceed the critical temperature of

TABLE 2

CALCULATED SOLUBILITY DATA

Temp., °C	Solubility product	Solubility of sulfide in moles per liter		
		pH = 3	pH = 7	pH = 11
		$Ag_2S_\alpha = 2Ag^+ + S^{--}$		
25	6.31×10^{-50}	2.12×10^{-12}	5.78×10^{-15}	2.15×10^{-16}
100	3.76×10^{-40}	5.45×10^{-10}	2.27×10^{-13}	1.20×10^{-13}
200	5.02×10^{-38}	5.42×10^{-8}	3.60×10^{-10}	4.70×10^{-11}
400	6.30×10^{-23}	9.73×10^{-6}	1.14×10^{-7}	5.01×10^{-8}
600	5.37×10^{-18}	1.62×10^{-4}	2.94×10^{-6}	2.21×10^{-6}
		$CdS = Cd^{++} + S^{--}$		
25	9.34×10^{-27}	8.43×10^{-7}	1.19×10^{-10}	8.55×10^{-13}
100	4.79×10^{-23}	3.22×10^{-6}	8.56×10^{-10}	1.06×10^{-11}
200	5.63×10^{-20}	9.48×10^{-6}	5.12×10^{-9}	2.43×10^{-10}
400	1.57×10^{-16}	3.35×10^{-5}	4.29×10^{-8}	1.25×10^{-8}
600	1.19×10^{-14}	6.88×10^{-5}	1.68×10^{-7}	1.09×10^{-7}
		$Cu_2S = 2Cu^+ + S^{--}$		
25	7.25×10^{-49}	4.79×10^{-13}	1.30×10^{-14}	4.85×10^{-16}
100	3.98×10^{-41}	2.58×10^{-10}	1.07×10^{-12}	5.70×10^{-14}
200	1.07×10^{-34}	6.96×10^{-9}	4.63×10^{-12}	6.06×10^{-12}
400	1.51×10^{-27}	2.81×10^{-7}	3.29×10^{-9}	1.45×10^{-9}
600	1.19×10^{-22}	2.12×10^{-6}	3.84×10^{-8}	2.88×10^{-8}
		$CuS = Cu^{++} + S^{--}$		
25	3.98×10^{-36}	1.74×10^{-11}	2.47×10^{-15}	1.76×10^{-17}
100	6.61×10^{-33}	3.78×10^{-10}	1.01×10^{-13}	1.24×10^{-15}
200	1.51×10^{-26}	4.90×10^{-9}	2.64×10^{-12}	1.25×10^{-12}
400	1.05×10^{-21}	8.78×10^{-8}	1.11×10^{-10}	3.24×10^{-11}
600	4.54×10^{-19}	4.25×10^{-7}	1.04×10^{-9}	6.73×10^{-10}
		$FeS_\alpha = Fe^{++} + S^{--}$		
25	5.13×10^{-18}	1.98×10^{-2}	2.82×10^{-6}	2.01×10^{-8}
100	1.26×10^{-16}	5.21×10^{-3}	1.39×10^{-6}	1.71×10^{-8}
200	2.00×10^{-15}	1.78×10^{-3}	9.61×10^{-7}	4.56×10^{-8}
400	3.80×10^{-14}	5.22×10^{-4}	6.69×10^{-7}	1.95×10^{-7}
600	2.00×10^{-12}	2.82×10^{-4}	6.89×10^{-7}	4.47×10^{-7}
		$HgS_{(r)} = Hg^{++} + S^{--}$		
25	1.88×10^{-53}	3.78×10^{-20}	5.37×10^{-24}	3.83×10^{-26}
100	3.98×10^{-44}	9.25×10^{-17}	2.47×10^{-20}	3.04×10^{-22}
200	2.69×10^{-38}	6.53×10^{-14}	3.52×10^{-17}	1.67×10^{-19}
400	1.30×10^{-27}	9.67×10^{-11}	1.24×10^{-13}	3.61×10^{-14}
600	6.92×10^{-23}	5.10×10^{-9}	1.24×10^{-11}	8.08×10^{-12}

TABLE 2—*Continued*

Temp., °C	Solubility product	Solubility of sulfide in moles per liter		
		pH = 3	pH = 7	pH = 11
		$MnS = Mn^{++} + S^{--}$		
25	2.29×10^{-12}	4.17	5.93×10^{-4}	4.23×10^{-6}
100	1.08×10^{-12}	4.84×10^{-1}	1.29×10^{-4}	1.59×10^{-6}
200	4.76×10^{-12}	8.68×10^{-2}	4.69×10^{-5}	2.22×10^{-6}
400	1.55×10^{-11}	1.06×10^{-2}	1.35×10^{-5}	3.94×10^{-6}
600	3.54×10^{-11}	3.76×10^{-3}	9.16×10^{-6}	5.95×10^{-6}
		$PbS = Pb^{++} + S^{--}$		
25	7.00×10^{-28}	2.30×10^{-7}	3.28×10^{-11}	2.34×10^{-12}
100	2.63×10^{-23}	2.38×10^{-6}	6.36×10^{-10}	7.85×10^{-12}
200	1.59×10^{-19}	1.58×10^{-5}	8.56×10^{-9}	4.06×10^{-10}
400	2.82×10^{-16}	1.42×10^{-4}	1.82×10^{-7}	5.31×10^{-8}
600	5.63×10^{-15}	4.73×10^{-4}	1.15×10^{-6}	7.50×10^{-7}
		$ZnS_{(sph.)} = Zn^{++} + S^{--}$		
25	1.52×10^{-24}	1.07×10^{-5}	1.53×10^{-9}	1.09×10^{-11}
100	1.20×10^{-21}	1.61×10^{-5}	4.29×10^{-9}	5.30×10^{-11}
200	3.31×10^{-19}	2.29×10^{-5}	1.24×10^{-8}	5.77×10^{-10}
400	1.51×10^{-16}	3.30×10^{-5}	4.22×10^{-8}	1.23×10^{-8}
600	4.52×10^{-16}	4.24×10^{-5}	1.03×10^{-7}	6.72×10^{-8}

the ore fluid receive some justification from investigations by Morey (13), which have shown that the solvent action of water does not change appreciably as the critical point is passed. At elevated temperatures the concept of pH becomes hazy due to the increased dissociation constant of water (14), and pH = 7 is no longer the neutral hydrogen ion concentration.

DISCUSSION

The data presented give economic geologists an up-to-date estimate of the role that simple sulfide solubilities can play in the transport of the ore metals. A comparison made by Krauskopf (7) might enable one to grasp more easily the significance of the solubility data. He has pointed out that a flow of solution equal to that of the lower Hudson River could deposit a ton of material in a year's time if the concentration of that material was 10^{-7} gm/liter. This flow seems excessive and Krauskopf (9) agrees that a concentration of 10^{-5} gm/liter might be a more realistic minimum to consider in discussions of ore solutions.

For the purposes of discussion a concentration of 10^{-5} gm/liter may be taken to correspond to one of 10^{-7} mole/liter. A consideration of the solubility data in Table 2 shows that under certain conditions some of the sulfides do satisfy this minimum requirement. Many, however, do not, and certainly the figures in Table 2 fail to explain satisfactorily the common

mineral associations of sulfide ore deposits. One must conclude that in nature the ore-bearing fluids are more complex. Probably the solubilities in liquid solutions are altered in one or more of the manners that have been mentioned. Garrels (4 and 5), Hemley (6), Krauskopf (7), Treadwell and Hepenstrict (15), and Treadwell and Schaufelberger (16) have attempted to consider some of these possibilities for Ag_2S, CuS, HgS, and PbS. On the other hand, it is quite probable that magmatic gases play a substantial role in the transport of ore metals, and an attempt to evaluate their role has recently been presented by Krauskopf (8).

The solubility data permit the following generalization regarding the simple solubilities of the sulfides:

1) The more acid solutions can universally carry more metal ion in solution at a given temperature than the alkaline solutions.
2) As the temperature rises the amount of metal ion in solution varies less with change in pH, especially in the alkaline region.
3) With the exception of the anomalous behavior of FeS and MnS, the concentration of the metal ions increases with temperature.
4) The relative solubilities of PbS and ZnS change at about 300° C with ZnS being the more soluble compound at low temperatures and PbS the more soluble compound above 300° C.
5) The solubilities of ZnS and CdS are similar and are virtually identical at 400° C.
6) The two copper sulfides are about equally soluble.

In conclusion, the limited application of these data is regretfully acknowledged. Barton (2) and Barnes and Kullerud (1) have indicated approaches that might be made to a fuller understanding of the ore fluids and ore transport. Unfortunately, the data necessary for a refined attack on these problems are in many cases not available.

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THE NATURE OF DAVIDITE[1]

ALICK W. G. WHITTLE

ABSTRACT

The Precambrian rocks of Australia contain a wider variety of davidites than has been found elsewhere in the world.

Investigation of davidite occurrences as an economic uranium ore over a number of years has revealed its many peculiar physical and chemical characteristics.

It has been shown to be a primary mineral generally associated with sodium-rich acidic igneous rock as replacement lode deposits, as disseminated replacement deposits, as fissure fillings of pneumatolytic origin and as an accessory mineral in pegmatites.

Its association with titania, both as regular and recognizable inclusions of rutile and ilmenite, and as the less apparent sub-microscopic titaniferous "framework," raises the question as to whether the generally accepted description and composition of davidite is valid.

INTRODUCTION

DAVIDITE is a uranium mineral of considerable economic value in Australia and it has been the subject of investigation by the Research and Development Branch of the South Australian Mines Department for several years. Most of this work was concerned with the Radium Hill deposits and included geological mapping, experimental ore-dressing and chemical treatment, with concurrent mineralogical studies.

Geologists also discovered davidites in other localities and the mineralogical studies were extended to include them. Many davidite localities are now known, and at present Australia may be said to have the widest range of varieties of this mineral. The only other known occurrence of davidite, that of the Tete district of Mozambique, was described in 1950 in a paper by Bannister and Horne (1).

The initial recognition of davidite was by Mawson at Radium Hill (8). Subsequently a special report was issued by the Mineragraphic Section of C.S.I.R.O., Melbourne, dealing with the ore-mineral complex of Radium Hill (6). This was followed some 5 years later by a composite report by several authors in a general bulletin dealing with uranium deposits in South Australia (4). Davidite was also discussed by the author in a paper in 1954 (11).

DAVIDITE LOCALITIES

The principal deposits occur in the northeast sector of South Australia and are indicated in Figure 1. Many minor deposits occur amongst those

[1] Published with the approval of the Director of Mines and Government Geologist, Adelaide, S. A.

shown on the map. The largest single deposit is that at Radium Hill where mining is in progress. Next in importance are those at Mount Victoria and Crocker Well, where mining may be carried out in the future. Other deposits, at present of an uneconomic nature, are also shown in Figure 1. That of the Houghton district is probably the largest of these.

GEOLOGICAL ENVIRONMENT

At Radium Hill, davidite occurs in extensive steeply dipping, near-parallel, flat lens-shaped lodes that occupy shear zones in tightly-folded structures in metamorphosed Precambrian rocks. The geology of Radium Hill was described by Sprigg (4) and Parkin and Glasson (9).

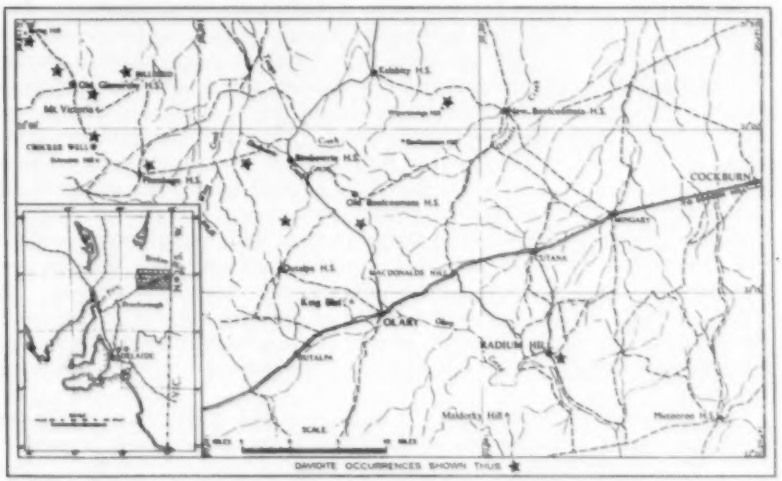

FIG. 1. Locality map showing davidite occurrences in South Australia.

The ore bodies are of hypogene origin and the uranium mineralization takes the form of a replacement lode deposit. The ore bodies consist of massive quartz, micas, feldspars and carbonates with hematite, ilmenite, rutile, davidite, sulfides and magnetite. The petrology and mineralogy of the ore deposit was described in 1954 by Whittle (4). A complex of hematite, ilmenite and rutile is thought to belong to an earlier stage of mineralization, the davidite to a later stage followed by sulfide emplacement.

The wall rocks are coarsely crystalline, micaceous quartzo-feldspathic gneisses, commonly separated from the ore by a shear zone of black biotite. Both ore and wall rocks are penetrated at intervals by igneous rocks such as hornblendite, dolerite, acid pegmatite and aplite.

The davidite ore bodies of the Mt. Victoria district are smaller and more scattered than those of Radium Hill. They are considered by Campana (2), to have been similar to the Radium Hill ore bodies, but were broken up into

scattered remnant lodes by granitic intrusion. The detached remaining portions of the shear zones enclose some weak ore veins, but most of the davidite is in sporadic distribution through the dark biotite-rich rock.

The Houghton davidite is of the disseminated replacement type and is therefore in contrast to those above. This davidite does not form as vein-like lodes, but exists as globular individuals (1–5 mm in size) that occur unevenly distributed within certain horizons of the Archaean gneisses of the neighborhood. These favorable horizons are characterized by dominant coarsely-crystalline albite, which invaded and largely replaced those beds containing abundant diopside and actinolite. The included disseminated davidite is genetically related to the selective albitization of the gneisses. This phenomenon was described by Webb and Whittle in 1954 (4).

Most other Australian davidites occur in quite different associations. The deposits of Crocker Well, Spring Hill and Outalpa Springs occur in the fissures and cracks of granite and quartzite, with micas, sagenitic quartz, apatite, thorian brannerite (10), betafite and ilmenorutile; this mineral assemblage is indicative of emplacement by the pneumatolytic action of gaseous emanations from magma. Albitization of country rocks, including the granite and associated feldspathized sediment, is a feature of these davidite deposits. These associations suggest davidite was part of a mineral assemblage concentrated in residual fluids after widespread sodium metasomatic alteration of rocks of this area. These highly siliceous fluids, charged with hyperfusible constituents, lanthanons, uranium, and other metals, penetrated rock fissures and deposited davidite, brannerite, ilmenorutile, etc., in a quartz vein medium. In order to classify the many local occurrences of davidite, those of this type are considered to be of pneumatolytic origin. Geological features of these and other davidite deposits of the Olary province have been described by Campana and King (3).

The davidites of Wiperaminga Hill, Billeroo and of the Barrier Ranges constitute a group characterized by their occurrence as accessories in pegmatites. Commonly, the davidite is coarse grained and pseudo-crystalline. The pegmatites are extensive, as for example in the Barrier Ranges, where they occur over several square miles and are parallel to the lineation of the Archaean gneisses and schists. These pegmatites possibly owe their origin to the same magmas that caused regional albitization of Archaean rocks of the district.

The most recently discovered davidite near Mt. Pleasant, some 30 miles northeast of Adelaide, is another one of pegmatite affinity. It occurs as an accessory, intergrown with rutile in quartz-oligoclase pegmatites penetrating Cambro-Ordovician schists. The pegmatite field is in proximity to granite which penetrates the schist.

Varieties of davidite from the Mt. Isa district of Queensland have also been examined. The occurrence of some of these was described by Lawrence (7), who considers them to be of metamorphic origin. The most recent discovery in this area is that of nodular davidite enclosed in albitized diopside granulite. This is a disseminated replacement occurrence which is similar to that of the Houghton davidite.

A broad classification of davidites in Australia, based on geological mode

of occurrence, may be stated as:

(1) davidite as a replacement lode deposit;
(2) davidite as a disseminated replacement deposit;
(3) davidite of pneumatolytic origin;
(4) davidite as an accessory in pegmatite;
(5) davidite of metamorphic origin (according to Lawrence).

ASSOCIATED MINERALS AND TEXTURAL RELATIONSHIPS

These features are most briefly described using the mode of occurrence as a means of grouping those that are comparable.

Davidite as a Replacement Mineral.—Davidite is in coarse granular association with quartz and bronze biotite at Radium Hill. Less abundant but variable amounts of feldspar, calcite, sulfides, ilmenite hematite, rutile and magnetite combine in complex intergrowth to make up the ore. The ore bodies are crudely lens-shaped, measure several hundred feet in length and depth, and vary in thickness from a few inches at the extremities, to about 10 feet at the broadest centers. Commonly the lenses are continuous with each other along the strike of the shears and down the dip of the shears, the junctions being occupied by narrow biotite-sericite zones of shear. At least some davidite occurs throughout the whole ore body and in commonly shared shear zones between lenses, but the bulk of it occurs in ore shoots that form the massive coarse-grained portions of the ore bodies.

In the shears and in the lower grade portions of the ore bodies davidite occurs sparsely with hematite, ilmenite, and rutile in the cores of augen-like structures. The augen consist of 1–5 cm. ovoidal segregations of biotite disseminated through the sheared sericitized rock and oriented in the direction of the axial plane of the ore body. The cores of the individual augen consist of the hematite-ilmenite-rutile complex which is progressively more completely replaced by davidite as the ore shoots are approached along the shear zone. These structures illustrate incipient uranium mineralization that reaches maturity in the coarse massive ore that constitutes the shoots.

High-grade ore typical of the ore shoots contains abundant massive coarse-grained davidite which, in polished section, is found to form a complex intergrowth with ilmenite, hematite, rutile and silicates, with sporadic subordinate magnetite, pyrite, chalcopyrite, and molybdenite. Davidite is xenomorphic, globular or veinlike, and penetrates the complex intergrowths of the iron-titanium oxide minerals, many embayed fragments of which remain as inclusions within the davidite (Fig. 2). Separated, but optically continuous residuals of rutile, hematite, and other minerals, enclosed in broad expanses of the host mineral, davidite, clearly indicate the pre-existence of the hematite-ilmenite-rutile-silicate complex. High magnification observation of areas of apparently homogeneous davidite clear of these inclusions, reveals the presence of a myriad of minute particles of rutile, minor hematite, and ilmenite. The search for homogeneous davidite has been without success. The electron micrographs made from the clearest davidite indicate inhomogeneity at very high magnification (Fig. 14).

These swarms of minute rutiles may indicate exsolution of titania from davidite due to supersaturation, which occurred during the replacement of the iron-titanium mineral complex.

At depth in the mine, davidite is subidiomorphic against hematite, which it replaces. The forms appear to be hexagonal and may therefore be, as suspected in other occurrences, simply hematite pseudomorphs. This is suggested by the observation that davidite penetrates tabular hematite in flat zones

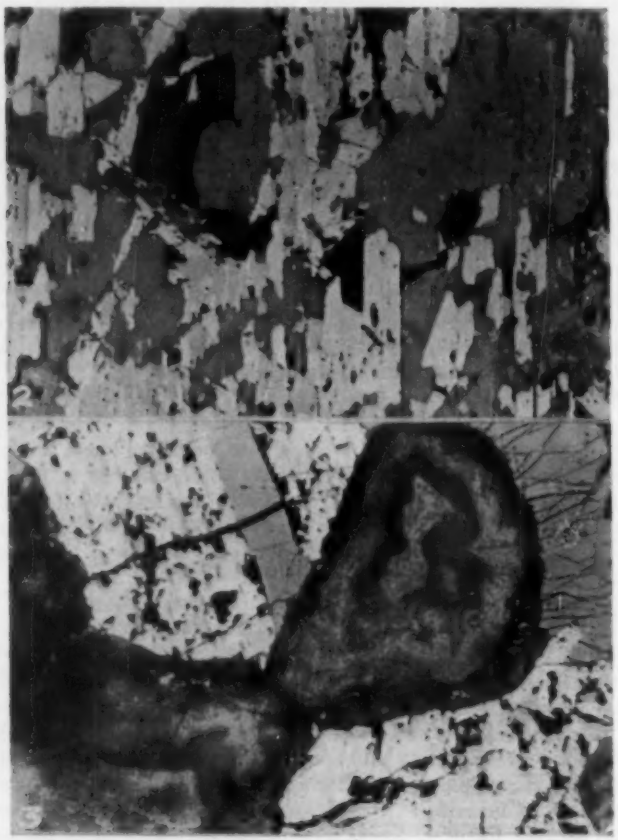

FIG. 2. No. 4 Level, Whip Lode Radium Hill. Davidite (gray) replacing hematite (white), rutile (light gray) and silicates (black). Detached embayed hematite within davidite still in optical continuity. × 240.

FIG. 3. Houghton. Davidite (dark gray) replacing hematite (white) with exsolution rods of ilmenite and rutile (light gray). Radial cracks extend from davidite into adjacent coarse rutile. Colloform texture of davidite accentuated by formation of secondary uranium minerals. × 240.

parallel to the basal pinacoid, forming lamellar replacement intergrowths along (0001), as does ilmenite by exsolution processes. Extended penetration and replacement would result in a hexagonal form of davidite as a pseudomorph after hematite.

This intricate textural association of davidite with the minerals stated is typical of all ore bodies at Radium Hill, and is characteristic of davidite that forms other local replacement ore bodies.

The dissected ore bodies in the granitic gneiss of the Mt. Victoria district contain davidite similar to that at Radium Hill. The gangue of these lodes is composed of dark-colored ellipsoidal masses of biotite, chlorite and sericite disposed in parallel orientation among granulated quartz and feldspar. These minerals, with abundant zircon, apatite, and sphene, are in proportions which indicate that they have resulted from the stressing of granitic gneiss, which is the host country rock. These stressed zones apparently formed traps for albite-rich hydrothermal fluids that affected much of the northeast province of South Australia. Petrographic study showed that these micaceous zones were replaced by significant amounts of albite and orthite as well as by variable amounts of davidite, rutile, hematite, magnetite and sulfides. Davidite grains are ovoidal or irregular in form and vary up to 10 cm in longest dimension. Characteristically, davidite replaces the centers of ellipsoidal clusters of micaceous minerals and is considered to be syngenetic with albite and orthite.

The davidite is not a pure mineral and polished sections of it exhibit the same mineral complex as in the Radium Hill ore. Davidite contains many coarse inclusions as well as chains of fine inclusions of rutile, hematite and titaniferous magnetite, many of which are at least subhedral. Besides these and skeletal remnants of micaceous minerals, there are swarms of minute rutiles less than 10 microns in diameter which may be exsolution particles from davidite.

Sulfides are prominent. Pyrite replaces micas along cleavages, whereas chalcopyrite and enargite occur as inclusions within davidite with corroded residuals of the rutile-hematite aggregate. Textures suggest rutile, hematite, and magnetite formed prior to davidite, as at Radium Hill, and were then replaced by it. This concept of two periods of mineralization, based on mineragraphic evidence, is supported by geological field evidence as described by Campana (2).

The finer grained globular davidite of the Houghton district is strictly confined to thin albitized horizons of the Archaean complex, thus forming low-grade ore bodies. Actinolite and diopside are prominent constituents of these gneisses and are the minerals commonly replaced by davidite. The only resemblance to lode formations is that there are minor fractures filled with extremely coarse actinolite and massive hematite in which there are 1–2 cm blebs of davidite.

Extremely large albite crystals dominate the uraniferous horizons of the actinolite-diopside gneisses, and are so disposed that the albite twin lamellae are perpendicular to the foliation. Residual diopside and actinolite, with significant amounts of sphene and apatite, form incomplete parallel bands through the albites and indicate the former rock structure. Albitized bands

vary in thickness from inches to several feet, and extend for long distances along the strike of the foliation. Davidite blebs, typically 2 mm in diameter are surrounded by radial expansion cracks and occur at close, but irregular intervals throughout the rock, being most abundant where albitization is most complete. Most davidite occurs in the residual diopside-actinolite aggregates within albite, replacing these minerals initially along intergranular boundaries, then extending within to form globular masses; some davidite is simply enclosed within albite.

Polished sections of these davidite globules reveal that they are unusually free of inclusions of other opaque minerals. They show a distinct internal colloform texture that is reflected in their external bulbous shape. Alteration to a fine anisotropic aggregate of carnotite, limonite and leucoxene, proceeds along the curving lines of the colloform structure producing rounded isotropic davidite residuals enclosed in extremely fine yellow-brown earthy material.

The rare inclusions found in these globules are mostly hematite particles of small size. Examination at high magnification reveals the presence of a myriad of minute particles a few microns in size, these appear to be hematite, rather than rutile.

The davidite found in rare fractures with coarse actinolite and hematite contains many inclusions of hematite and rutile ranging from 0.1–2.0 mm in diameter. Hematite and rutile are commonly euhedral and in coarse granular intergrowth with each other. Hematite contains exsolution lamellae of ilmenite and of rutile. Davidite replaces these euhehra along curving interfaces, commonly penetrating and forming a core within the crystals (Fig. 3). In weathered rocks, the davidite within the hematite or rutile crystals escapes alteration and that outside is quickly converted to a brown earthy secondary mineral complex.

Davidites of Pneumatolytic Origin.—These are xenomorphic granular davidites, generally less than an inch in diameter. They are intergrown with quartz, felspar, micas, thorian brannerite, rutile, etc., and fill fractures in granites and quartzites. The main occurrences are at Spring Hill, Outalpa Springs and parts of the Crocker Well area. These davidites are all inhomogeneous and resemble those of the Radium Hill lodes in appearance.

Spring Hill davidite contains numerous rutile and ilmenite inclusions of about 5 microns in diameter as well as smaller chalcopyrites. The ilmenite-rutile aggregates are inequidimensional, and lie, over considerable areas, with their elongate forms in parallelism (Fig. 4). These composite davidite individuals vary up to several centimeters in diameter and are enclosed in quartz and feldspar traversed by radial cracks emanating from the davidite.

Outalpa Springs davidite occurs as 2–5 cm nodules in quartzite. It has a very impure appearance in polished section due to abundant inclusions of silicates, hematite, rutile, ilmenite and magnetite which constitute in all, some 60 percent of each individual nodule. Davidite was the last mineral to enter these aggregates of iron-titanium oxide minerals and silicates, which exist within the davidite as highly embayed, irregular-shaped, separated groups in optical continuity (Fig. 5). This results in a textural similarity with the Radium Hill davidite.

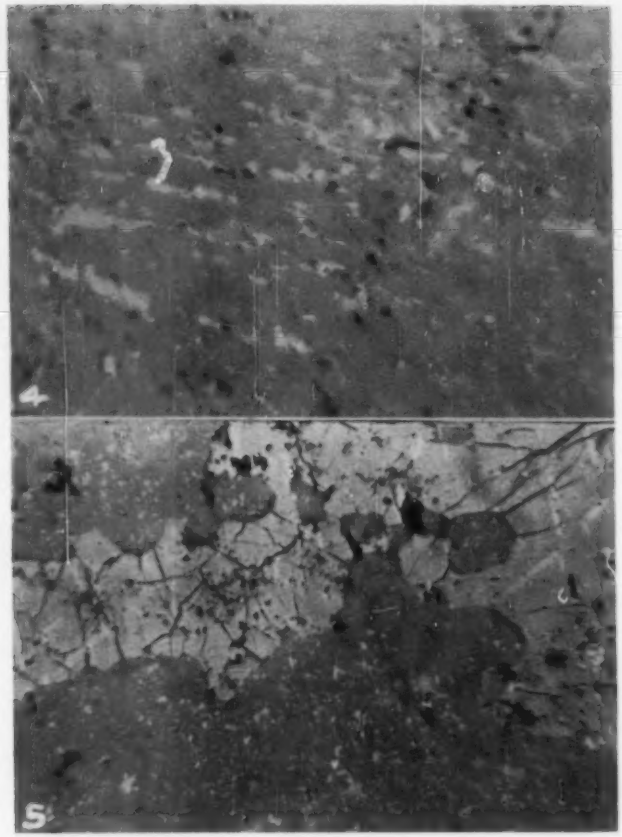

FIG. 4. Spring Hill. Inclusions (light gray) which are aggregates of rutile and ilmenite, oriented in parallelism in davidite (darker gray). × 1,200.

FIG. 5. Outalpa Springs. Davidite (dark gray) replacing a magnetite-rutile intergrowth. Detached fragments in davidite are in optical continuity with parent mass. × 240.

Similar examples may be selected locally within the Crocker Well prospect. In all varieties of pneumatolytic davidite, high magnification examination of the apparently homogeneous davidite between inclusions, discloses the presence of swarms of ultrafine rutile and subordinate hematite inclusions below 1 micron in size.

Davidites of Pegmatitic Origin.—Davidites from the various pegmatite localities were examined in incident light and were found to be comparable.

In some cases, as for example at Billeroo and at Wiperaminga Hill, the davidite occurs in rough crystals, the form of which is difficult to determine.

In the Barrier Ranges and at Mt. Pleasant, the davidite is coarsely massive. In all cases, in addition to their distinctive mode of occurrence, these davidites are highly lustrous, black, and have perfect conchoidal fracture. Thus, when all types of davidite are compared, this kind most nearly approaches a typical uranium rare-earth mineral in macroscopic appearance and other physical features.

Microscopic examinations confirm the relatively pure nature of pegmatitic davidite, in that it is unusually free of inclusions of silicates and of the various iron-titanium oxides. Sulfides are absent.

Sizeable inclusions of hematite, rutile, etc., constitute less than 1 percent of the mineral mass, but ultrafine inclusions below 1 micron in size are present, as in all davidites. It is difficult to assess their bulk in relation to the davidite mass, but it appears to be of the order of 5 percent; they are mainly rutile.

A distinctive form of secondary mineral development is characteristic of this group and is visible only by microscopic aid. Thin fracture lines,1–2 microns in width, traverse the davidite commonly in irregular, but in some cases in regular, patterns. On either side of these lines a zone of alteration, due to the formation of carnotite, leucoxene, etc., extends irregularly to a distance of up to 10 microns, producing a mass darker in color than the unchanged davidite.

Where a regular pattern of lines of alteration is followed, the structure is suggestive of cleavage directions, perhaps belonging to the pre-metamict form of the mineral (Fig. 6). This regularity of pattern is to be considered in relation to the rhythmic pattern commonly produced by pegmatitic davidites on autoradiograph plates (Fig. 7).

Davidites of Other Origins.—The deposits of Mozambique described by Bannister and Horne (1), and those of Queensland described by Lawrence (7), are located in geological environments rather different from those of South Australia.

Lawrence suggests that the main occurrences in Queensland are of regional metamorphic origin and that davidite is widespread in small amounts in schist and gneiss. There is so far no known equivalent of this mode of occurrence in South Australia.

Davidite from near the Mary Kathleen ore body in the Mt. Isa district of Queensland, which has been examined by the author, has geological affinities comparable with davidite of Houghton. In this case nodular davidite is disseminated through highly albitized calc-silicate rock.

PHYSICAL PROPERTIES OF DAVIDITE

The description of the physical properties of davidite is rendered difficult because of the ever present intergrowths of other minerals. The pegmatitic davidite may be used as the type material since it is the purest form available.

Davidite is a brittle, highly lustrous black mineral with a conchoidal fracture but with no regular crystal form or cleavages. The hardness, based on comparative tests, is 5–6 and the specific gravity lies within the range 4.4–4.5. It is weakly magnetic.

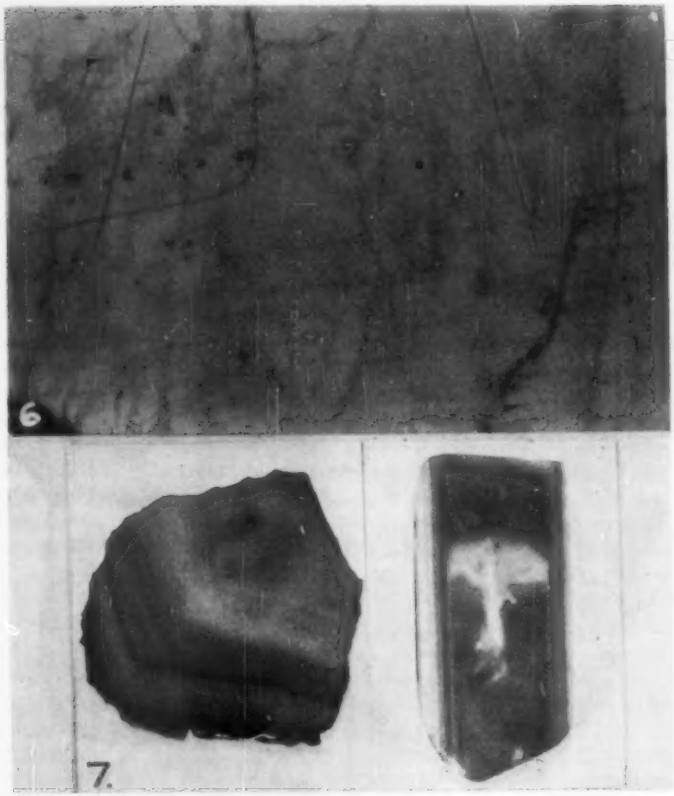

FIG. 6. Wiperaminga Hill. Secondary minerals (dark gray) forming in davidite (lighter gray) along two directions which might be pre-metamict cleavage planes. × 240.

FIG. 7. Natural size. Wiperaminga Hill. Prints of autoradiographs of portions of davidite "crystals" to illustrate two types of rhythmic or zonal variation in radioactivity.

Davidite assumes a fine polished surface that is light gray in color in reflected light. In transmitted light it is opaque except along very thin edges where it may be deep red-brown and translucent.

It is isotropic with complete extinction and has a refractive index above 2.2. The reflectivity values compared with pyrite in polished sections of davidite are:

for white light in air	18.2%
for red light in air	15.9%
for red light in oil	6.5%

TABLE 1

Mozambique (Kerr & Holland)		Mozambique		Mt. Isa		Billeroo No. 1		Broken Hill		Houghton		Rutile (A.S.T.M. Index)		Jutland Davidite	
d Å	I	d Å	I	d Å	I	d Å	I	d Å	I	d Å	I	d Å	I	d Å	I
6.71	2	6.77	1	6.81	2	6.89	f	6.74	1	6.77	1			6.75	1
5.16	1	5.16	2	5.16	1	5.16	2	5.16	3					5.17	1 B
								4.86	2					4.85	1
		4.74	1	4.73	3			4.73	2	4.74	2 B				
4.47	2														
4.15	6	4.15	3 B	4.15	3 B	4.16	2 B	4.15	2 B	4.17	2 B			4.14	2 B
						3.80	2								
				3.48	4			3.48	3	3.47	3				
3.40	9	3.40	7	3.42	8	3.42	8	3.40	8	3.41	8			3.40	8
		3.35	2	3.35	3	3.35	2			3.35	2				
3.23	8	3.26	4	3.25	5	3.26	7	3.25	7	3.25	9	3.245	100	3.24	8
						3.12	2								
3.05	8	3.06	6	3.06	5	3.06	6	3.06	5	3.06	4			3.05	6
		3.00	5	3.00	4	3.00	4	3.00	5	3.00	4			2.99	4
2.87	10	{2.89	10	2.89	10	2.90	10	2.89	10	2.89	10			2.89	10
		{2.84	6	2.85	6	2.85	7	2.85	7	2.85	6			2.84	7
		2.76	1	2.75	4	2.75	3	2.75	3	2.76	4			2.74	2
		2.70	f	2.70	f			2.70	1	2.70	2			2.69	1
2.62	3	2.63	3	2.64	3	2.64	4	2.63	3	2.63	3			2.63	4
		2.59	2	2.59	1	2.60	2	2.59	2	2.59	2			2.59	2
		2.52	1	2.52	2									2.52	f
2.48	8	2.473	5 BB	2.478	4 B	2.483	5 B	2.475	4 B	2.480	4 B	2.489	41	2.484	5
														2.469	4
2.42	3	2.425	4	2.431	4	2.428	3	2.425	4	2.426	3			2.421	4
						2.364	1								
								2.300	1	2.292	f	2.297	7		
				2.277	2										
2.25	8	2.246	6	2.251	6	2.248	7	2.246	7	2.249	5			2.244	7
2.19	3	2.189	2	2.191	1	2.191	2	2.193	1	2.191	2	2.188	22	2.185	3
		2.136	5	2.139	4	2.139	4	2.138	5	2.139	4			2.136	6
2.10	2														
		2.065	f	2.073	1	2.067	2			2.055	2 B	2.054	9	2.063	1 B
2.03	1	2.030	2	2.031	2 B	2.024	1	2.028	1 B	2.032	1 B			2.031	2
1.96	2	1.958	1	1.960	2	1.956	2	1.960	1	1.966	1			1.959	2
1.91	4	1.912	4	1.912	3	1.914	2	1.913	3	1.914	3			1.913	3
		1.890	2			1.889	2							1.895	1
				1.866	2			1.863	f						
1.84	2	1.841	2	1.847	2	1.847	1	1.847	1	1.849	2			1.846	2
1.80	6	1.802	4	1.803	4	1.803	4	1.801	4	1.802	3			1.800	4
1.78	1	1.775	1	1.777	1	1.778	2	1.773	1	1.778	1			1.777	2
		1.740	1	1.746	1 B	1.744	1							1.735	1 B
1.70	9	{1.706	3	1.706	4	1.706	3	1.705	3	1.704	3			1.705	3
		{1.691	3	1.688	3	1.688	5	1.688	4	1.689	4	1.687	50	1.685	5
		1.650	2	1.651	2	1.651	2	1.646	1	1.649	1			1.651	1
		1.625	2	1.624	2	1.624	2	1.624	2	1.624	2	1.624	16	1.624	2
		1.611	2	1.614	2	1.616	1							1.614	f
1.60	5	1.595	5	1.599	6	1.599	5	1.598	5	1.600	5			1.600	6
1.57	1	1.566	1	1.573	1	1.567	2	1.571	1	1.572	1			1.572	1
1.55	1	1.541	2 B	1.542	1 B	1.546	2	1.547	2 B	1.548	1 B			1.549	1 B
1.51	3	1.506	2	1.507	1	1.510	2	1.505	3	1.511	2			1.511	2
		1.483	f	1.482	f							1.480	8	1.479	2
		1.462	f	1.463	f			1.465	2					1.465	1
				1.452	f			1.450	1	1.450	1	1.453	6	1.451	2
1.44	7	1.435	4	1.437	5	1.437	6	1.436	5	1.440	4			1.437	4
		1.418	1	1.418	1	1.421	1	1.420	1	1.420	1			1.420?	1
		1.390	f			1.387	2	1.390	1	1.396	1			1.392	1
1.38	4	1.374	2	1.374	2	1.378	2	1.373	2	1.376	1			1.374	1
		1.360	2	1.360	1	1.361	2	1.359	2	1.362	2	1.360	16	1.360	2
		1.345	1			1.348	2	1.346	1 B	1.348	1	1.347	7	1.349	2
		1.297	1					1.306	f			1.305	1	1.326?	1
														1.318?	1
														1.300	1

B = Broad.
BB = Very broad.
f = Faint.

The ratio of uranium to total lanthanons does not have a marked effect upon reflectivity value or color.

The properties such as fracture, luster and density in the hand specimen, are greatly influenced by the abundance and grain size of the various inclusions

contained by different davidites. The pegmatite varieties are relatively free of these, but davidites of Radium Hill, Mt. Victoria and elsewhere commonly become duller and grayer, and assume a hackly fracture as they become progressively more crowded with rutile or other minerals.

Most davidite is massive, but there are a few occurrences of davidite "crystals" in the Olary district. These forms are incomplete, inconsistent, large, rough and not suited to goniometric work. It is thought furthermore, that they are pseudomorphs, as in the case of those at Radium Hill. It is also significant that when a batch of "crystals" from these localities is examined by mineragraphic and autoradiographic methods, many are found to be irregular, or rhythmic zonal growths of the hematite-ilmenite-rutile complex with davidite.

A feature of these "crystals" is the property of zoned or rhythmic variation of radioactivity (Fig. 7). The comparative examination of an autoradiograph with its corresponding polished section, shows that rhythmic variation in intensity or radioactivity is due to at least two phenomena. One of these is that illustrated in Figure 6, in which alteration products of lower radioactivity have formed along parallel directions within the davidite. The other, more significant in relation to the question of validity of crystal form and chemical composition, is the presence of numerous minute rutile inclusions aligned in roughly parallel zones. According to the density of inclusions per unit area, the radioactivity of the davidite host is reduced to a greater or lesser degree, thus resulting in a zoned autoradiagraphic pattern.

Mr. J. L. Farrant of C.S.I.R.O. prepared electron-micrographs of several polished sections of both Radium Hill and Houghton davidite An example of these is illustrated in Figure 14; it shows an area of davidite clear of microscopically visible inclusions. At the high magnification at which this surface was photographed, its inhomogeneity is apparent and probably due to a myriad of minute rutiles of submicroscopic size distributed through the davidite. The interpretation of the electron micrographs is important in consideration of the chemical behavior of davidite during leaching, which is described below.

X-RAY INVESTIGATIONS OF DAVIDITE

Diffraction analysis was attempted on all the varieties of davidite mentioned in this paper, first using the natural mineral and secondly using the heated mineral. Iron filtered cobalt radiation was used in all cases. The heating procedures involved keeping the mineral at 950° C in a nitrogen atmosphere for four hours and then allowing it to cool slowly in a stream of nitrogen.

These procedures, as well as those involving examinations of rutile, were carried out by Arthur Tynan, Mineralogist, Department of Mines, South Australia. From his observations the data of Table 1 were compiled.

CHEMICAL PROPERTIES OF DAVIDITE

Davidite may be regarded as an iron-uranium-rare earth titanate containing small amounts of chromium and vanadium, which substitute for iron, as well as small amounts of thorium, which substitutes for uranium. The data

in Table 2 indicate the wide variation in composition in davidites due to these substitutions.

These data were obtained from the examination of carefully selected material freed from extraneous mineral as far as it was practicable. This procedure involved hand picking, heavy liquid and magnetic separations. In spite of this, mineragraphic examination of each sample analyzed, indicated the presence of microscopic, physically-inseparable grains of silica, silicates, hematite, ilmenite and rutile. Attempts to estimate these by micrometric

TABLE 2

ANALYSES OF DAVIDITE

	A	B	C	D_1	D_2	E	F	G
UO_2*	5.6	2.3	2.8	8.8	4.3	3.6	7.7	1.5
$Ln_2O_3 + ThO_2$	8.2	11.6	6.4	7.0	11.3	8.8	7.6	12.8
TiO_2	49.8	50.7	53.6	47.0	53.0	49.8	45.3	49.0
Fe_2O_3	20.7	29.8	17.6	31.3	25.3	29.9	32.1	6.8
FeO**								23.9
Cr_2O_3	0.7	0.7	1.5	0.6	0.4	1.1	1.3	
V_2O_3	0.4	1.2	6.1	1.5	1.8	2.7	0.6	3.1
Al_2O_3, ZrO_2 etc.	4.3	1.7	4.2	0.7		1.1	2.0	
PbO	1.0	0.5	0.9	0.9	0.7	0.7	1.5	0.1
Mn_3O_4								0.3
CaO								0.7
SiO_2	4.6	0.2	4.4	0.9	1.4	1.3	0.2	0.1
Loss on ignition	3.6	0.3	0.9			nil	0.5	
H_2O (+ 100° C)				1.2	1.2			
Insol in H.F.				nil	0.5			

A. Davidite from fractured quartzite, Spring Hill: Analyst D. Bowditch.
B. Davidite from pegmatite, Billeroo: Analyst D. Bowditch.
C. Davidite from lodes, Mt. Victoria: Analyst D. Bowditch.
D_1. Davidite from David Lode, Radium Hill: Analyst J. D. Hayton.
D_2. Davidite from Whip Lode, Radium Hill: Analyst J. D. Hayton.
E. Davidite from pegmatite, Broken Hill: Analyst D. Bowditch.
F. Davidite from calc-silicate rock, Mt. Isa: Analyst D. Bowditch.
G. Davidite from pegmatite, Mt. Pleasant: Analyst J. D. Hayton.

* The actual state of oxidation of uranium in davidite is uncertain and difficult to determine. Evidence suggests that it is as UO_2.

** Ferrous iron was not determined in most cases because of the uncertainty of the state of oxidation of uranium, vanadium and chromium, hence it is usually expressed as Fe_2O_3.

analysis and to subtract equivalent amounts from the analyses were not very successful because of their small sizes, irregular distribution, and frequent difficult identification during traverses when mounted on a Shand integrating stage.

Davidite is a complex oxide mineral of which the essential components are titania, iron oxide and varying proportions of uranium, and the lanthanon oxides. The remaining components are minor substitution groups, radiogenic lead and non-hygroscopic water. Silica, alumina, and calcium oxide are regarded as impurities in the samples.

The total of the lanthanon and uranium oxides is approximately a constant value and may be regarded as a characteristic of davidites. Hence, those davidites with high uranium content are of relatively low rare-earth content

and vice versa. If there is a substitution series of davidites due to interchange of uranium and rare-earth metals, then Billeroo and Mt. Pleasant davidites are nearest to the rare-earth end member.

The changes that occur in davidite during the acid treatment used to remove its uranium, reveal phenomena that make uncertain how much of the titania in the analytical figures may be assigned to the composition of davidite. Evidence on this question is supplied by electron micrographs, by X-ray studies, and by mineragraphic examination of the residue from davidite after extraction of its components by chemical leaching. Chemical plant residues contain granular material amongst the fine sludge of silicates and precipitated titania, which, when examined in non-polarized incident light, has an appearance not unlike that of davidite (Fig. 13). The uranium content of these residues is virtually nil. This granular residue of davidite was studied by progressive examination of Billeroo davidite during a leach with 3N HNO_3 at 80° C, extending over a period of 30 hours. Leaching was continued to 96 percent extraction of the uranium. Samples were taken of the solids and of the leach liquor every three hours. The solids were briquetted, polished, and examined in incident light and the liquors analyzed to enable the preparation of extraction rate graphs.

The progressive change in davidite, the major component of the solids, is illustrated in Figures 8 to 13, which show the internal structure of the grains as intersected in the polished surface of briquettes prepared at the several stages of leaching. Initial attack caused peripheral embayment, followed by the gradual formation of a replica of davidite as the front of chemical attack moved towards the centers of the grains (Figs. 9, 10, 11, 12). This replica, examined with crossed nicols in incident light, appeared to be a homogeneous material with the resinous red-brown internal reflections of an aggregate of very fine rutile.

Fine globular precipitated hydrated titania of 5 microns diameter is present in the sludge, and may be seen in the bakelite mounting medium amongst the leached davidite grains. It is a transparent, honey-yellow, poorly reflectant material, quite distinct from the titania that makes up the replicas. The position of the front of chemical attack within the grains is indicated in the illustrations by the dark line, which shrinks inwards with progressive leaching. The granular particles in the final residue are of the same dimensions and angular shapes as the original davidite and they retain, at normal orientations, the unattacked inclusions of rutile, hematite and silicates.

Optical and X-ray studies showed that these replicas are aggregates of minutely crystalline rutile. The subdued peaks of their X-ray diffraction pattern suggested a poor degree of crystallinity. A strong normal rutile pattern was given by the replica material after it was heated for several hours at 900° C.

These conditions of leaching, therefore, resulted in davidite being dissociated with the solution of all its major components, leaving only a replica of rutile similar in size and shape to the original davidite. Titania forms 51 percent of the davidite of which 21 percent went into the leach liquor and 30 percent remained to form the residual davidite replica. With different

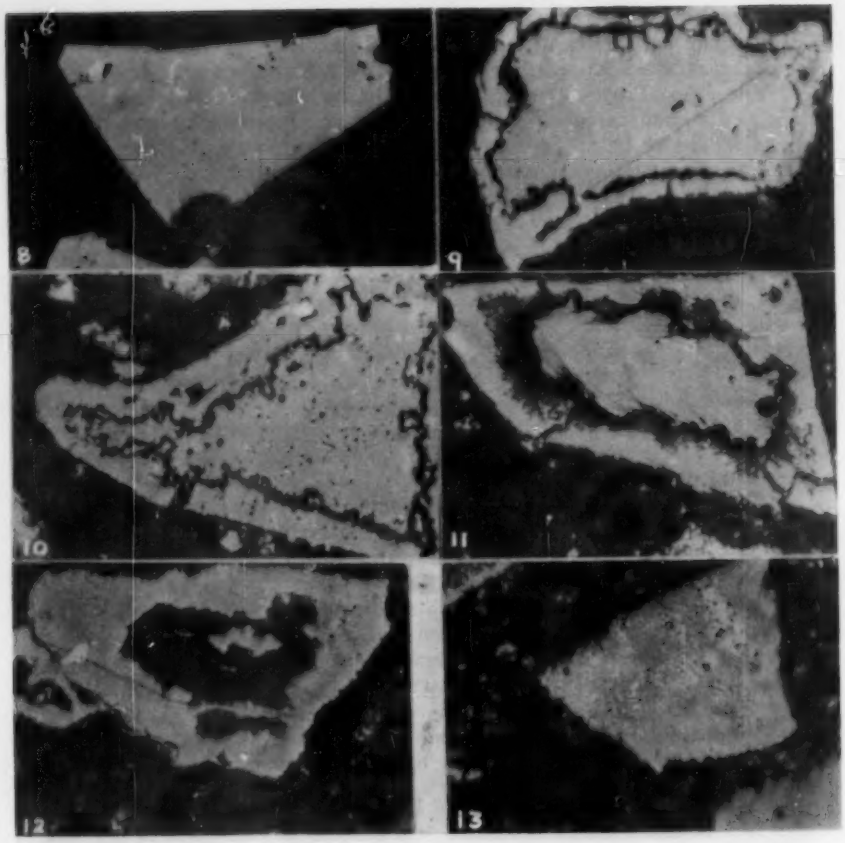

FIG. 8. Natural Billeroo davidite. A ground particle as used in leaching experiments. It has conchoidal fractured edges and minute inclusions of rutile and hematite (white) and of silicates (black). × 300.

FIG. 9. Residue after 9 hours leaching. × 300.

FIG. 10. Residue after 15 hours leaching. Original rutile and hematite inclusions remain in place in outer leached zone. × 300.

FIG. 11. Residue after 21 hours leaching. × 300.

FIG. 12. Residue after 27 hours leaching. × 300.

FIG. 13. Residue after 30 hours leaching. This is the final product that still retains its hematite and rutile inclusions and a shape and appearance comparable to that in Figure 8. × 300.

conditions of leaching the results vary. Investigations carried out with both Mozambique and Billeroo davidite using stronger acid and longer leaching times resulted in less perfect rutile replicas and finally, in their general disintegration. At high acid strengths the rutile replica is completely dissolved.

It is nevertheless significant, that provided gentle leaching conditions are employed, the elements of davidite may be rendered soluble, leaving behind a facsimilie of the original mineral. This unusual phenomenon suggests, that to ascertain the true composition of davidite, as normally analyzed with results such as listed in Table 2, the relationship of davidite to its rutile replica must be ascertained. This, unfortunately, appears to be an impossible task, since the weight ratio of replica to davidite is dependent upon leach acid strength. The broad indication given above, which is the result obtained by the gentlest leaching conditions necessary to remove the essential components of davidite, suggests that something like 30 percent of the original davidite is in physical rather than chemical combination with that which is the true radioactive mineral.

If this large proportion of titania pre-existed as a microscopically invisible component in davidite, then an amount equivalent to it must be subtracted from the analyses. Alernatively the replica may have formed during the progress of chemical dissolution of the davidite.

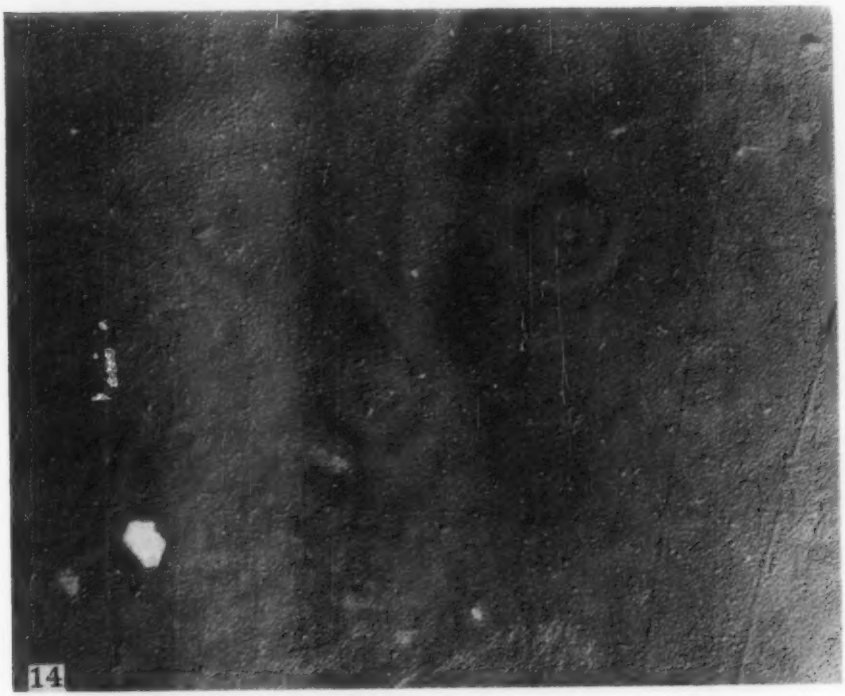

FIG. 14. Davidite replica, Houghton, unetched. The long thin ridges are polishing scratches. The surface is inhomogeneous due to pitting caused by numerous rutile ? inclusions within the davidite. This indicates the impossibility of selecting pure mineral for analysis. × 20,000.

Natural davidite, freed from inclusions and examined by X-ray diffraction analysis failed to produce any kind of recognizable crystal pattern. The same davidite, after having been heated for at least 5 hours at 900° C in a nitrogen atmosphere, produced the standard davidite diffraction pattern, amongst which were the principal lines of rutile. All davidites examined behaved in this way.

Hence rutile can be shown to be present in davidite after heat treatment, and to be left from davidite after acid leaching, even though it was not detected in the natural untreated mineral. It seems unlikely that this fine-grained rutile replica of davidite resulted from chemical precipitation from the titanium-rich leach liquor during dissolution of the davidite because the only titania precipitated was as a sludge, which was proved by X-ray analysis to be a hydrate.

The presence of sub-microscopic rutile in davidite has to be accepted on the basis of this experimental evidence. It has also to be accepted, that in its natural state, this rutile cannot be detected by X-ray analysis. It is most difficult to account for this state of affairs. It may be suggested that the rutile replica is present in natural davidite as a sort of "framework" amongst which the real davidite is distributed. In this fine desseminated form, the rutile, as well as the davidite, exists in the metamict state and produces a rutile diffraction pattern only after crystallinity is restored by the heating procedures. Its behavior can be compared with that of very weakly radioactive minerals such as orthite and cyrtolite, which return to normal after heat treatment.

The apparent complexity of davidite was suggested by Dixon and Wylie in 1951 (5), as a result of the abnormal distribution the lanthanons obtained in analyses which they made on South Australian davidites. They suggested as an explanation that more than one mineral species may be present in davidite.

Chemical investigations indicate therefore, that the definition of davidite and its composition is not a matter of easy solution, but that considerably more research is required to understand it completely.

CONCLUSIONS

The remarks concerning the chemical characteristics of davidite indicate the difficulty of assigning to it, a definite composition. One may conclude that davidite is perhaps not a finite mineral species, but that it could consist of a mechanical mixture of two or even more minerals, which are intimately associated at submicroscopic sizes.

However, davidite as presently accepted, is a mineral of hypogene origin genetically related to acidic primary rocks or their derivatives, especially when these are highly sodic in composition. In general, the geochemical conditions of davidite formation are those in which uranium, titanium, rare earths and iron are important constituents of the hydrothermal solutions, which contain sufficient fluidizing volatiles to facilitate permeation of compact crystalline Archaean rocks at considerable depth.

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SOME ASPECTS OF THE ORIGIN OF THE IRONWOOD IRON-FORMATION OF MICHIGAN AND WISCONSIN[1]

N. KING HUBER

CONTENTS

	PAGE
Abstract	82
Introduction	83
Acknowledgments	84
General geology	84
Regional stratigraphy	84
Stratigraphy of the Ironwood iron-formation	85
General description	85
General features of the iron-formation members	86
Lateral continuity of the iron-formation members	87
Alteration of the iron-formation	90
Primary mineralogy and composition of the Ironwood iron-formation	90
Location of material studied	90
Iron-formation minerals and rock types	91
Carbonate-rich rocks	91
Silicate-rich rocks	96
Magnetite-rich rocks	98
Hematite-rich rocks	100
Pyrite-rich rocks	100
Miscellaneous rock types	101
"Sweepings bed"	101
Fragmental or conglomeratic rocks	102
Argillite	103
Distribution of rock types	103
Origin of the Ironwood iron-formation	108
Sedimentary facies of iron-formation	108
Environmental implications of facies concept	108
Relation of chemical environments to physical parameters	109
Marine versus non-marine environment	110
Origin of the chert	111
Source of the iron and silica	112
Tectonic framework of sedimentation and depositional history	114
References	116

ABSTRACT

The Ironwood iron-formation of the Gogebic Range of Michigan and Wisconsin is made up of several rock types, each of which is characterized by a different iron-rich mineral: hematite, magnetite, pyrite, iron carbonate, or iron silicate (minnesotaite, stilpnomelane). Where the Ironwood iron-formation is relatively unaltered the Plymouth, Norrie, and Anvil

[1] Publication authorized by the Director, U. S. Geological Survey.

members consist of wavy-bedded magnetite and silicate-rich rocks, whereas the Yale and Pence members consist of even-bedded carbonate, silicate, magnetite, and pyrite-rich rocks. These rock types represent primary facies of the iron-formation that were deposited under differing physical and chemical conditions during a period of continuous iron-rich sedimentation.

Animikie sedimentation in the Gogebic district began with the deposition of sandstone and dolomitic limestone in a shallow sea advancing over a low-lying land mass of lower Precambrian granite and greenstone. Continued advance of the sea, with effective separation of clastic material near shore, permitted the dominantly chemical sedimentation of the iron-formation in somewhat deeper water. The development of an off-shore basin with partially restricted circulation would have facilitated such deposition. Minor fluctuations in the physical and chemical conditions within the depositional environment are reflected in the differing facies of the iron-formation. Deposition of the iron and silica-rich chemical sediments was terminated by increased tectonism and the deposition of the thick sequence of slates and graywackes of the Tyler formation.

INTRODUCTION

THE Gogebic Range of Michigan and Wisconsin (Fig. 1) has long been an important producer of iron ore in the United States. Since ore was first mined in 1883, extensive surface exploration, diamond drilling and mine workings have provided a great deal of information on the geology of the region. The principal reports on the geology are those by Irving and Van Hise (26), Van Hise and Leith (48), Hotchkiss (22), and Aldrich (1). Aldrich presents an excellent history of the development of the range and a review of the literature up to 1929. The Gogebic Range is also included in a summary of the geology of the Lake Superior region by Leith, Lund, and Leith (36).

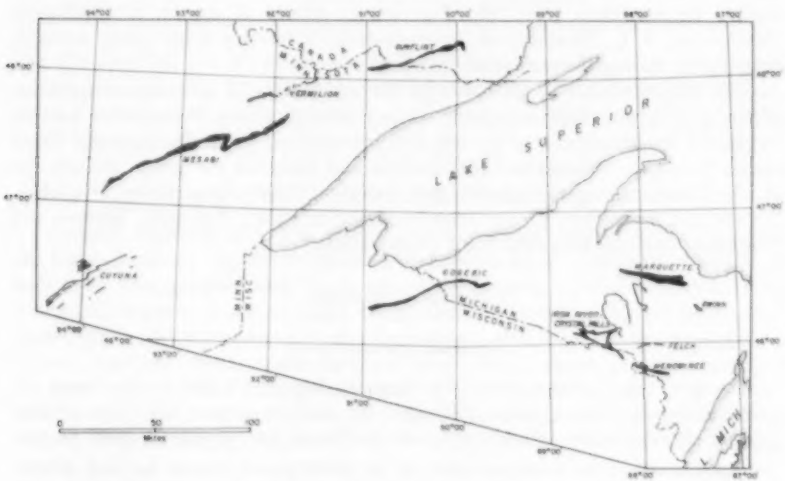

FIG. 1. Index map showing location of Gogebic Range in relation to other Lake Superior districts.

The banded iron-rich rocks which make up the Ironwood iron-formation of the Gogebic Range have long been recognized as being of sedimentary origin and, to a large extent, the result of chemical precipitation. Many different suggestions have been made, however, as to the source of the materials involved, the mode of transportation, the nature of the original formation, and the geochemical and tectonic framework of the sedimentary environment. The present study applies some relatively new concepts of chemical sedimentary environments to the problem of the origin of the Ironwood iron-formation.

The study was begun with the hope that enough unoxidized and relatively unmetamorphosed material could be found in the areas of established stratigraphy to permit determination of the primary lithology of each of the stratigraphic units of the iron-formation. This hope has been only partly realized, for although the rocks that make up the iron-formation are only slightly metamorphosed in a large part of the district, the iron-formation has been extensively oxidized to depths of more than 4,000 feet in the area of active mines. It is nevertheless possible in many places to determine the approximate primary mineralogy of various facies of the iron-formation and to postulate physical and chemical sedimentary environments for each type.

ACKNOWLEDGMENTS

This paper is a by-product of a regional study of the Lake Superior iron ranges being made by the U. S. Geological Survey in cooperation with the Geological Survey Division of the Michigan Department of Conservation. Additional assistance for this study was provided by the S. F. Emmons Memorial Fellowship, which the writer held while at Northwestern University during the academic year 1953–54. H. L. James of the U. S. Geological Survey and A. L. Howland of Northwestern University made many valuable suggestions during the course of the study.

The writer wishes to acknowledge the complete and generous cooperation of the geologists, engineers, and mining companies of the district and to emphasize his indebtedness for aid and information from this source. Companies that have contributed information and material for study include the M. A. Hanna Company; Jones and Laughlin Steel Corporation; Oglebay, Norton and Company; Oliver Iron Mining Company; Pickands, Mather and Company; and the Republic Steel Corporation.

GENERAL GEOLOGY

Regional Stratigraphy

The general stratigraphy of the Gogebic Range (Table 1) has been established by Hotchkiss (22), Aldrich (1), and Atwater (4). The formations of the Animikie series [2] rest with profound unconformity upon granite

[2] The Huronian nomenclature of older reports on the Gogebic district has been dropped in preference to the use of Animikie series as advocated by James for other parts of the upper peninsula of Michigan (James, H. L., 1958, Stratigraphy of pre-Keweenawan rocks in parts of northern Michigan: U. S. Geol. Survey Prof. Paper 314-C, p. 27–44).

and greenstone of early Precambrian age. Because of early Animikie erosion, the Sunday quartzite and Bad River dolomite are only locally preserved and in most parts of the area the Palms quartzite and Ironwood iron-formation lie directly upon the pre-Animikie basement complex. Atwater (4) has demonstrated that the iron-formation and the overlying Tyler formation are unconformable and that the Tyler and Copps formations are stratigraphically equivalent. Sedimentary rocks and extrusive volcanic rocks of the Keweenawan series rest unconformably upon the Animikie series.

Post-Animikie intrusives are represented by gabbro near Mellen, Wisconsin, and related Keweenawan rocks in the western part of the range and by many diabasic dikes cutting the Animikie strata throughout the range.

TABLE 1

GENERALIZED STRATIGRAPHIC SUCCESSION IN THE GOGEBIC DISTRICT. (MODIFIED FROM ATWATER (4))

Upper Precambrian	Keweenawan series	Sandstone, conglomerate, extrusives, and intrusives
		——(major unconformity)——
Middle Precambrian	Animikie series	Tyler formation (Copps in east). As used by Atwater (4) Pabst conglomerate member
		——(unconformity)——
		Ironwood iron-formation Palms quartzite
		——(unconformity)——
		Bad River dolomite Sunday quartzite
Lower Precambrian		——(major unconformity)——
		Granite Greenstone

The Presque Isle granite of the eastern part of the range has been called post-middle Huronian by Allen and Barrett (3) and by Atwater (4), but is considered to be pre-Animikie (pre-Huronian of older reports) by James (1958, personal communication).

Stratigraphy of the Ironwood Iron-Formation

General Description.—The term "iron-formation" has long been used in the Lake Superior region to denote iron-rich rocks of sedimentary origin as well as a stratigraphic unit made up of such rocks. Hotchkiss (22) used structural features, which to some extent also reflect mineralogical differences, to group the rocks that make up the Ironwood iron-formation into two general types: "wavy-bedded ferruginous chert" and "even-bedded ferruginous slate."

The "wavy-bedded ferruginous chert" type of iron-formation is characterized by irregular beds and lenses of granular or oolitic chert, a fraction of an inch to several inches thick, which are separated by thin laminae of more evenly bedded iron-rich material. The iron-rich laminae consist largely of iron oxides, silicates, and carbonate, together with some fine-grained interstitial chert.

In the "even-bedded ferruginous slate" type, the beds are generally extremely regular and finely laminated. The chert in this rock is generally dense or flinty although locally it is granular or oolitic. The term "slate" as used by Hotchkiss (and in the mining district in general) denotes a thin-bedded, fine-grained rock, commonly with good parting parallel to the bedding but does not necessarily indicate the presence of true slaty cleavage or argillaceous composition. Most of the "slaty" material consists of iron-rich carbonate and silicate and interstitial chert, all of chemical sedimentary origin.

On the basis of the predominance of one of these rock types over the other, Hotchkiss subdivided the Ironwood iron-formation into five members. The five members are, from youngest to oldest:

Anvil ferruginous chert member
Pence ferruginous slate member
Norrie ferruginous chert member
Yale member—interbedded ferruginous cherts and ferruginous slates
Plymouth ferruginous chert member

The contacts between the various members of the iron-formation are commonly gradational and difficult to define, particularly where the iron-formation has been extensively oxidized. In addition, the "ferruginous chert" and "ferruginous slate" terminology is somewhat misleading as each member of the iron-formation embraces a wide variety of rocks not readily characterized by these terms. Nevertheless, the fivefold subdivision of the Ironwood iron-formation on the basis of the predominance of wavy-bedded material or even-bedded material appears to be valid for much of the district.

General Features of the Iron-formation Members.—Some of the general features of the various members of the iron-formation are summarized here. More detailed descriptions are given by Hotchkiss (22) and by Aldrich (1).

Starting with the oldest, the base of the Plymouth member consists of dense granular chert and jasper with numerous clastic quartz grains. The basal contact is generally sharp and is marked by the presence of the chert and jasper, neither of which is found in the underlying Palms quartzite. The abundance of clastic quartz grains in the iron-formation diminishes upward so that within several feet above the base clastic quartz is almost completely absent. In general, clastic quartz is scarce throughout the rest of the iron-formation. The zone of clastic quartz in a chert matrix at the base of the Plymouth has been termed the "sweepings bed" (1, p. 158). In places the "sweepings bed" contains concentric concretion-like structures as much as 2 or 3 inches in diameter, which are similar to the algal structures on the Mesabi Range described by Gruner (20, p. 38). Where these structures are present this zone is often called the "gnarled conglomerate."

An even-bedded carbonate-rich unit of iron-formation, the so-called "footwall-slate" of the Plymouth member, lies several feet above the base of the member and is in general only a few feet thick. It is fairly continuous throughout the range although it cannot be identified in all drill holes or sections.

The upper part of the Plymouth consists of wavy-bedded granular cherty iron-formation with a few zones of even-bedded iron-formation.

The succeeding Yale member consists dominantly of even-bedded iron-formation with minor granular chert sections. Pyritic carbonaceous slate occurs in the lower part of the Yale member. The stratigraphy of the Yale member is somewhat complicated by the "great bedding fault" which can be traced for much of the district and which lies almost wholly within or adjacent to the Yale member (22, p. 504).

The Yale member grades upward into the Norrie member, which, like the Plymouth member, is dominantly wavy-bedded granular-cherty iron-formation with only minor even-bedded sections.

The contact between the Norrie and the overlying Pence member is commonly marked by an extensive fragmental zone in which the fragments are composed entirely of iron-formation. This fragmental zone, plus variations in the thickness of the Norrie member, caused Hotchkiss to postulate the presence of a disconformity between the Norrie member and the overlying Pence member. The Pence member is dominantly even-bedded iron-formation although in some parts of the district a fairly thick granular-cherty zone occurs near the middle of the unit.

The uppermost member, the Anvil, consists mostly of wavy-bedded, granular-cherty iron-formation with numerous fragmental zones. The upper part of this member, however, does contain a fairly thick and extensive even-bedded zone.

Lateral Continuity of the Iron-formation Members.—Mine workings and drill core information obtained since 1919 have served to confirm Hotchkiss' subdivision of the Ironwood, at least within the main mining district from Iron Belt, Wisconsin, to Wakefield, Michigan (Fig. 2). Beyond the area of active mining, west of Iron Belt and east of Wakefield, both lack of continuous surface outcrops and the scarcity of good core or other exploration data make it difficult to evaluate the continuity of the various members of the iron-formation.

In the eastern part of the mining district an additional complicating factor is presented by the Sunday Lake fault (22, p. 539). Drill core data are incomplete in the area just west of the fault, and it is difficult with the available information to delineate the individual members of the iron-formation, which is strongly deformed both by folding and by intrusion of diabasic dikes and sills.

East of the fault, the iron-formation has not undergone appreciable deformation and can easily be divided into units similar to those in the main part of the mining district. In the Sunday Lake mine at Wakefield, Michigan, five distinct units are present, which are similar both in general thickness and in textural and structural properties to the fivefold division present west of the fault. The upper granular-chert unit, however, is truncated by the pre-Keweenawan unconformity and the amount of iron-formation which has been removed is unknown. On the basis of the similarity of these units to those to the west it would appear that the Plymouth, Yale, Norrie, Pence and the lower portion of the Anvil are all present in the Sunday Lake area. The total

thickness of iron-formation preserved under the pre-Keweenawan unconformity is also very nearly equivalent to that farther to the west. This interpretation is illustrated by the solid lines in Fig. 3.

Many company geologists and mining engineers on the range believe, however, that each of the five units thickens rapidly to the east in the general vicinity of the Sunday Lake fault and that only a small part of the iron-formation has been preserved under the Keweenawan unconformity in the Sunday Lake area. In this view, only the Plymouth and the lower portion

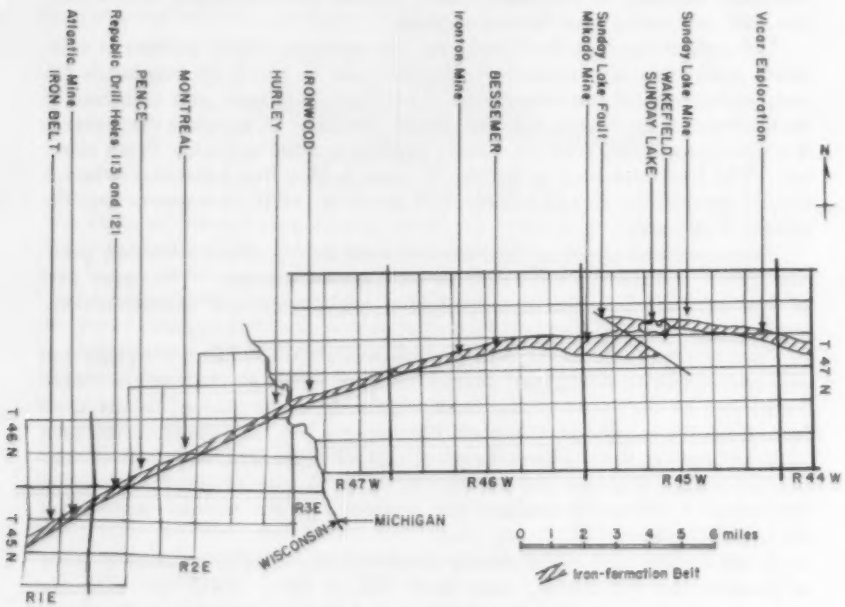

FIG. 2. Index map of main part of the Gogebic Range showing location of places and features mentioned in text.

of the Yale have been preserved, and the "footwall-slate" in the Plymouth member has increased in thickness from several feet in the main part of the range and about twenty feet at the Mikado mine to about one hundred feet at the Sunday Lake mine, some four miles east of the Mikado. The total Plymouth likewise will have increased from a maximum of 200 feet west of the fault to 350 feet at the Sunday Lake mine. This interpretation is illustrated by the dashed lines in Figure 3. Although the writer prefers the first interpretation, the second interpretation cannot be ruled out on the basis of the present study.

Whichever viewpoint is accepted, further difficulties are presented east of the Sunday Lake mine where duplications due to faulting may be present. At the Vicar exploration, about three miles east of the Sunday Lake mine, about 900 feet of iron-formation were penetrated in a diamond drill hole (Vicar No. 1201), but division into units comparable in nature and thickness to the normal five units does not seem possible. Only one section of typical granular-cherty rock, about 100–150 feet thick, is located about 300 feet from the base of the formation. If this granular chert unit is equivalent to the Plymouth,

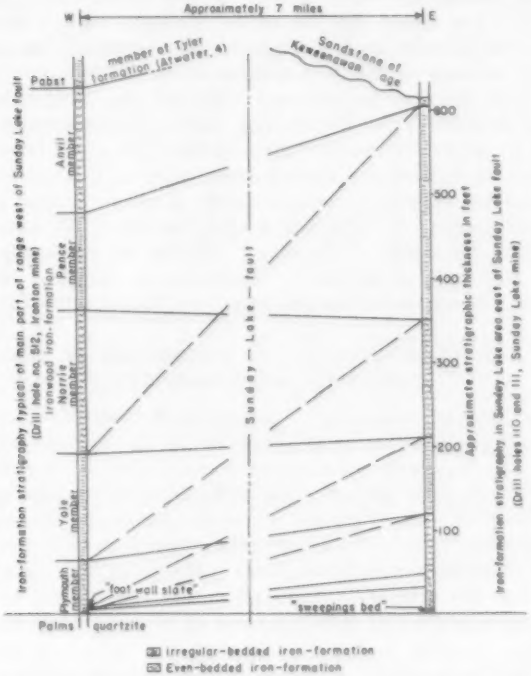

FIG. 3. Diagram illustrating alternate interpretations of iron-formation stratigraphy in the Sunday Lake area.

then either the lower part of the Plymouth in this area consists of a large slaty silicate and carbonate unit, or a wedge of such material has entered from the east. If the granular chert is equivalent to the Norrie, then the Plymouth has lost its normal granular character in this area. Many company geologists in the area believe that the Plymouth member extends to the top of this wavy-bedded granular chert unit. In spite of the correlation difficulties, the Vicar core presents an excellent assemblage of relatively unaltered rock types for iron-formation facies studies.

Alteration of the Iron-Formation

In the major part of the range, from the vicinity of Iron Belt, Wisconsin, to several miles east of Wakefield, Michigan, the iron-formation has undergone little structural disturbance, other than regional tilting, except in the area of the Sunday Lake fault. Contact metamorphism related to the intrusion of numerous diabasic dikes and sills is local. In the western part of the range, intrusion of gabbro and associated granitic rocks resulted in metamorphism and structural disturbance of the iron-formation. The eastern end of the iron-formation belt beyond the Vicar exploration also is structurally disturbed.

James (29) has shown that the entire Michigan portion of the Gogebic district is in the chlorite zone of regional metamorphism, the lowest grade appearing on his map of the metamorphic zones of the upper peninsula of Michigan. This zone can be extended westward into Wisconsin to an area between Iron Belt and Tyler Forks Creek (several miles west of area shown on map, Fig. 2) where evidence of higher metamorphic grade begins to appear.

In addition to regional and contact metamorphism the iron-formation has locally been altered by other processes, chiefly oxidation of iron minerals and leaching or replacement of silica, which have resulted in the formation of the commercial iron ore bodies of the range. Within the producing part of the range, from just west of Montreal, Wisconsin, to just east of Wakefield, Michigan, the iron-formation has generally been extensively oxidized.

PRIMARY MINERALOGY AND COMPOSITION OF THE IRONWOOD IRON-FORMATION

The term "primary mineralogy," as used here, refers to minerals formed either by direct precipitation or by diagenesis in the bottom sediments after deposition. The diagenetic environment is considered as part of the depositional environment even though great differences in various physical and chemical parameters may be present above and below the depositional interface. The problem arises as to whether the origin of certain minerals can be attributed to diagenesis or metamorphism. Magnetite and some of the iron silicates fall into this category. Although certain criteria will be considered, the two processes grade into each other and an absolute distinction is not always possible.

As this study is essentially an attempt to determine the primary mineralogy of the iron-formation as a key to the environmental conditions existing at the time of deposition of the formation, minerals of recognizable metamorphic origin and other products of secondary alteration, including the iron ores themselves, are excluded from this discussion.

Location of Material Studied

The areas of iron-formation that have undergone neither high degrees of metamorphism nor other secondary alterations are limited to (1) the area centered around Pence, Wisconsin, located between a zone of high metamorphism to the west and a zone of high oxidation to the east, and (2) the area around the Vicar exploration east of Wakefield, Michigan, located between a zone of high oxidation to the west and a zone of structural disturbance

TABLE 2

CHEMICAL ANALYSES OF CARBONATE-RICH IRON-FORMATION

	A	B	C	D	E
SiO_2	39.26	40.09	32.87	30.62	29.35
Al_2O_3	2.88	2.23	2.46	0.41	0.70
Fe_2O_3	0.63	9.96	4.78	0.46	4.41
FeO	24.94	25.84	30.84	34.50	39.51
MgO	4.62	2.79	3.58	4.41	3.81
CaO	4.62	0.50	0.62	1.45	2.10
Na_2O	0.00	0.03	0.00	0.00	0.00
K_2O	0.00	0.40	0.00	0.00	0.00
H_2O^-	0.11	0.56	0.28	0.03	0.06
H_2O^+	1.23	1.80	1.69	0.02	2.79
TiO_2	0.07	0.23	0.27	0.02	0.01
CO_2	20.46	14.38	20.94	27.03	16.37
P_2O_5	0.11	0.13	0.09	0.10	0.14
S	0.04	0.01	0.09	0.07	0.06
V_2O_3	—	0.01	0.00	—	—
MnO	1.23	1.25	1.33	0.93	1.02
C	0.07	0.05	0.45	0.06	0.08
Total	100.27	100.26	100.29	100.11	100.41
Less 0 for S	0.02	0.01	0.05	0.04	0.03
	100.25	100.25	100.24	100.07	100.38

A. Chert-carbonate iron-formation (HJ-100-52; Lab. No. 52-1595). Drill hole No. 1201, 1,224 to 1,241 feet; SE¼SE¼ sec. 12, T. 47 N., R. 45 W., Gogebic County, Michigan. Analyst: Lucile N. Tarrant, U. S. Geological Survey.

B. Chert-carbonate iron-formation (NKH-103-53; Lab. No. 53-2106CD). Drill hole No. 121, 301 to 313 feet; SE¼SE¼ sec. 31, T. 47 N., R. 2 E., Iron County, Wisconsin. Analyst: Lucille M. Kehl, U. S. Geological Survey.

C. Chert-carbonate iron-formation (NKH-104-53; Lab. No. 53-2107CD). Drill hole No. 121, 660 to 674 feet; SE¼SE¼ sec. 31, T. 47 N., R. 2 E., Iron County, Wisconsin. Analyst: Lucille M. Kehl, U. S. Geological Survey.

D. Chert-carbonate iron-formation (HJ-99-52; Lab. No. 52-1594). Drill hole No. 1201, 786 to 798 feet; SE¼SE¼ sec. 12, T. 47 N., R. 45 W., Gogebic County, Michigan. Analyst: Lucile N. Tarrant, U. S. Geological Survey.

E. Carbonate-silicate iron-formation (HJ-98-52; Lab. No. 52-1593). Drill hole No. 1201, 651 to 665 feet; SE¼SE¼ sec. 12, T. 47 N., R. 45 W., Gogebic County, Michigan. Analyst: Lucile N. Tarrant, U. S. Geological Survey.

to the east. The majority of the specimens examined in this study as representing the "least altered" iron-formation came from these two areas.

Iron-formation Minerals and Rock Types

The major minerals that comprise the bulk of the unaltered or weakly metamorphosed iron-formation are few; namely chert (quartz), iron carbonate, magnetite, hematite, minnesotaite, and stilpnomelane. Chlorite and pyrite are widespread but are generally of minor importance. With the exception of quartz, all the minerals are iron-rich and reflect changing environmental conditions in a period of continuous iron-rich sedimentation.

Individual parts or samples of iron-formation can be classified according to the dominant minerals present, but there is a great deal of intergradation between rock types and almost all intermediate varieties can be found.

Carbonate-rich Rocks.—Carbonate-rich rocks form one of the more im-

portant lithologic types of iron-formation. The carbonate-rich rocks are almost all even-bedded with individual beds of uniform thickness, the fine laminations reflecting slight differences in mineralogical composition. Most commonly the carbonate-rich layers are interbedded with thin chert layers that average about a quarter of an inch in thickness. The chert layers now consist of microcrystalline quartz, which occurs also as interstitial material with the carbonate. Megascopically the chert is dense or flinty and usually is gray or greenish. Locally the chert stringers are nodular or irregularly shaped.

The carbonate material is iron-rich, approaching siderite in composition; it is discussed in more detail in later paragraphs.

Magnetite is common, both disseminated or in clusters throughout the carbonate material and in discrete layers within the carbonate beds.

Silicate minerals (minnesotaite, stilpnomelane, rarely chlorite) commonly occur intimately admixed with carbonate rather than in separate layers. Within a given series of layers the carbonate-silicate ratio varies considerably between adjacent units. Analysis E, Table 2, represents an example where the average silicate percentage exceeds that of the carbonate; all ratios are not only possible but are commonly found.

Hematite is rarely if ever present in the carbonate-rich rocks unless secondary oxidation has taken place.

Stylolites, parallel or sub-parallel to the bedding and typically of small amplitude, are common in the carbonate-rich rocks, both within carbonate layers and at the contact between carbonate and chert layers.

Table 2 gives five chemical analyses of carbonate-rich iron-formation. Analyses, A, B, C, and D are of chert-carbonate rock. Analysis E is of carbonate-silicate rock that contains slightly more silicate than carbonate; it is included here for comparative purposes and may be considered an intermediate type. The samples analyzed consisted of split diamond drill core of as much as ten feet of stratigraphic section. Each analysis, therefore, represents the average for a rock that is actually made up of thin beds of vastly different character.

The important minerals present in these samples have been determined in thin section, so that the approximate mineralogical composition of the analyzed rocks can be calculated by the following procedure, in which several arbitrary assumptions are made:

1. In these samples hematite is negligible and all Fe_2O_3 is therefore assigned to magnetite and balanced by an equivalent quantity of FeO.
2. All CaO and MnO are combined as carbonate. The remaining CO_2 is balanced by FeO and MgO in the same ratio as that in the bulk analysis after subtraction of FeO for magnetite.
3. Remaining FeO and MgO are assigned to minnesotaite [$(Fe,Mg)_3Si_4O_{10}(OH)_2$] in the same ratio as determined for carbonate. In the samples for which calculations were made, stilpnomelane is minor and other iron or magnesium-rich minerals negligible.
4. Remaining SiO_2 is assigned to quartz.
5. Other oxides—alumina, phosphate, alkalies, etc.—are listed as excess constituents. In the samples for which calculations were made this category does not exceed 5 percent of the total and in some is 1 percent or less.

TABLE 3

APPROXIMATE MINERALOGICAL COMPOSITION, IN WEIGHT PERCENT, OF CARBONATE-RICH IRON-FORMATION AS CALCULATED FROM ANALYSIS IN TABLE 2

	A	B	C	D	E
Carbonate[1]	49.6	35.9	52.4	67.2	40.8
Quartz	31.8	34.7	29.5	29.7	5.8
Silicate[2]	14.5	10.2	6.5	1.7	46.3
Magnetite	0.9	14.4	6.9	0.7	6.4
Excess constituents[3]	3.4	5.0	5.0	0.7	1.0

[1] Composition of carbonate shown in Table 4.
[2] Calculated as minnesotaite [$(Fe,Mg)_3Si_4O_{10}(OH)_2$].
[3] Includes Al_2O_3, K_2O, Na_2O, P_2O_5, and minor elements.

Step 2 in the procedure, which determines the composition of the carbonate material (and indirectly the silicate material), is the most arbitrary, although the assignment of all CaO and MnO to carbonate is reasonable as no other calcium or manganese-rich minerals are important constituents of the iron-formation. The method of assignment of FeO and MgO to the carbonate may not be entirely valid, but some arbitrary ratio is necessary as both ferrous iron and magnesium are shared by more than one mineral in unknown quantities. The ratio assumed here seems reasonable, although the iron mag-

TABLE 4

APPROXIMATE COMPOSITION OF CARBONATE, IN MOLE PERCENT, FROM CARBONATE-RICH IRON-FORMATION

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
$FeCO_3$	58.9	74.6	76.8	76.2	72.8	81.2	75.0	84.2	84.8	77.5	78.9	71.4	75.8	85.7	89.5
$MgCO_3$	19.7	17.3	17.0	17.5	13.2	14.1	14.9	12.3	12.0	12.6	12.5	8.4	16.4	12.5	7.8
$CaCO_3$	17.7	2.7	2.3	4.2	10.1	2.3	2.7	2.1	1.8	5.1	3.4	4.4	7.3	1.8	2.0
$MnCO_3$	3.7	5.4	3.9	2.1	3.9	2.4	7.4	1.4	1.4	4.8	5.2	15.8	0.5	—	0.7
Weight percent of carbonate in total sample															
	49.6	35.9	52.4	67.2	40.8	63.6	44.6	48.9	56.9	70 0	77.1	67.7	49.7	55.3	67.2

A. Chert-carbonate iron-formation, Gogebic Range, Mich. (Analysis A, this paper).
B. Chert-carbonate iron-formation, Gogebic Range, Mich. (Analysis B, this paper).
C. Chert-carbonate iron-formation, Gogebic Range, Mich. (Analysis C, this paper).
D. Chert-carbonate iron-formation, Gogebic Range, Mich. (Analysis D, this paper).
E. Silicate-carbonate iron-formation, Gogebic Range, Mich. (Analysis E, this paper).
F. Carbonate iron-formation, Gogebic Range, Mich. (26, p. 192, analysis II).
G. Carbonate iron-formation, Gogebic Range, Mich. (26, p. 192, analysis III).
H. Carbonate iron-formation, Gogebic Range, Mich. (26, p. 192, analysis IV).
I. Carbonate iron-formation, Gogebic Range, Mich. (26, p. 192, analysis V).
J. Chert-carbonate iron-formation, Iron River district, Mich. (27, p. 257, analysis A).
K. Carbonate-rich layer from iron-formation, Iron River district, Mich. (27, p. 257, analysis C).
L. Carbonate-rich layer from iron-formation, Iron River district, Mich. (27, p. 257, analysis D).
M. Carbonate iron-formation, Gunflint district, Minn. (26, p. 192, analysis VIII).
N. Carbonate iron-formation, Marquette district, Mich. (47, p. 337, analysis I).
O. Carbonate iron-formation, Marquette district, Mich. (47, p. 337, analysis II).

nesium partition coefficient would not necessarily be the same in the carbonate as in, for example, the iron-rich silicates. Problems concerning the composition of the silicate minerals are discussed in the section on silicate-rich rocks.

The approximate mineralogical compositions of the analyzed material, as calculated by the above method, are listed in Table 3. Some of the alumina, which has all been placed in the miscellaneous category, may occur in the

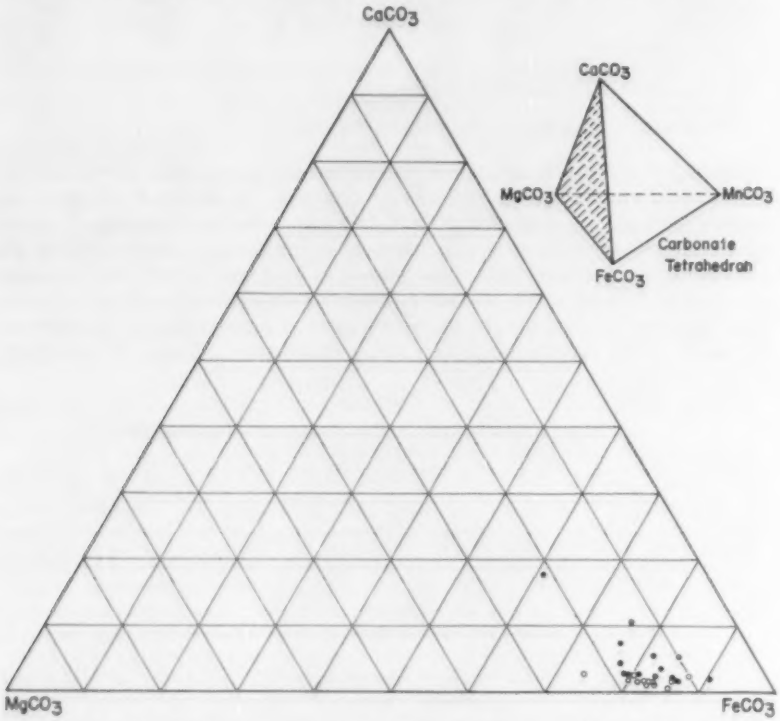

FIG. 4. Approximate composition of iron-formation carbonate as projected on $CaCO_3$-$MgCO_3$-$FeCO_3$ face of carbonate tetrahedron. Dots indicate samples listed in Table 4. Circles indicate compositions calculated from partial analyses.

silicate material if stilpnomelane or chlorite are considered. The rest of the alumina may occur as kaolin although kaolin has not been specifically identified in this study.

Table 4 gives the approximate composition of the carbonate, in mole percent, as calculated from the analyses of the five carbonate-rich samples of iron-formation presented in Table 2. Also included in Table 4 are carbonate compositions calculated for ten other samples of carbonate rich iron-formation from various sources. Figure 4 illustrates the composition of these samples

as plotted on a $CaCO_3$-$MgCO_3$-$FeCO_3$ diagram. Figure 5 illustrates the variation in $MnCO_3$ content as plotted on a plane connecting the $CaCO_3$-$MgCO_3$-$FeCO_3$ face with the $MnCO_3$ apex of the carbonate tetrahedron. In addition to the carbonate compositions from Table 4, Figures 4 and 5 also

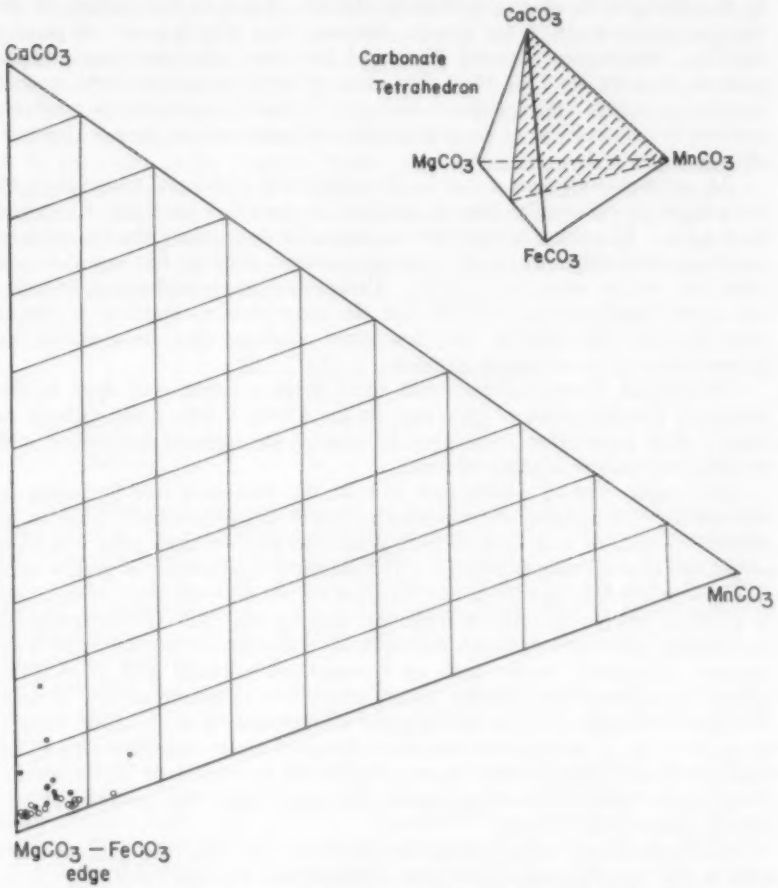

FIG. 5. Approximate composition of iron-formation carbonate plotted to indicate variation in $MnCO_3$. Dots indicate samples listed in Table 4. Circles indicate compositions calculated from partial analyses.

include compositions calculated from six partial analyses provided by The Cleveland-Cliffs Iron Company [3] and from six additional analyses provided by H. L. James.[4] The plot assumes that the carbonate occurs as a single

[3] B. H. Boyum, The Cleveland-Cliffs Iron Company, written communication, April, 1955.
[4] H. L. James, U. S. Geological Survey, written communication, April, 1955.

phase although this may not actually be the case. Kulp, Kent, and Kerr (33) note that complete substitution is observed between Fe^{++} and Mg^{++} in the carbonate lattice but that substitution of Ca^{++} in $FeCO_3$ is limited to about 10 percent. The presence of Ca^{++} beyond the substitution limit would result in the intergrowth of two carbonate phases. Whether this occurs in the samples under study is not known, but only two contain over 10 percent $CaCO_3$. Substitution between Mn^{++} and the three other end-members appears to be complete (33, 34). The close grouping of all but three or four samples is notable and it appears that iron-formation carbonate is relatively uniform in composition, at least where the carbonate makes up a major percentage of the rock.

An attempt was made to verify the calculated carbonate composition by the method of differential thermal analysis as described by Kulp, Kent, and Kerr (33). However, because it was impossible to separate the fine-grained carbonate from other thermally reactant material, such as the iron-rich silicates, the results were inconclusive. Preliminary x-ray diffraction patterns also were unsatisfactory, probably for the same reason: inability to obtain pure material. In addition, very few x-ray reference data are available for known mixtures of carbonate minerals.

Silicate-rich Rocks.—Silicate-rich rocks form a major rock type in the Ironwood iron-formation. They are, on the whole, a little more difficult to classify than some other rock types because of the intimate association and variable percentages of other minerals.

The major type of silicate-rich rock in the Ironwood iron-formation is thin-bedded or laminated and contains carbonate and magnetite in addition to silicate. Typically it is light to dark green but may be dark gray if a high percentage of magnetite is present. The chemical composition of such a rock is shown in Table 2, sample E, and its approximate mineralogical composition in Table 3, sample E. The silicate-rich rocks grade with all mineralogical proportions into rocks in which carbonate or magnetite is the dominant iron mineral. Magnetite occurs both as disseminated material and as discrete layers. Granule-bearing silicate rocks, which are abundant on the Mesabi and Gunflint Ranges (35, 20, 28, 49), are also present on the Gogebic Range. Some of the wavy-bedded iron-formation discussed under magnetite-rich rocks contains silicate granules and some iron-formation beds near Tyler Forks Creek contain stilpnomelane aggregates that might have been granules before metamorphism (28, p. 268).

Minnesotaite and stilpnomelane are the two most important silicate minerals in the iron-formation. Because minnesotaite was not established as a mineral species until 1944 (19), studies of the Ironwood prior to that date have identified this iron silicate as another mineral, usually an amphibole. In the so-called actinolitic slates of Irving and Van Hise (26), minnesotaite or stilpnomelane is the dominant silicate, at least in the relatively unmetamorphosed rocks. Stilpnomelane also has only recently been recognized as an important constituent of various iron-formation rocks of the Lake Superior district (17, 18, 20, 28, 49).

Minnesotaite is essentially a ferrous iron analogue of talc (19; 51, p. 365).

Pure iron minnesotaite [$Fe_3Si_4O_{10}(OH)_2$] has been synthesized by Flaschen and Osborn (11) but in natural occurrences magnesium substitutes for some of the ferrous iron. In the chemical analysis of natural minnesotaite given by Gruner (19) the Fe^{++}/Mg ratio is about 5.4. In a partial analysis by D. W. Scott (presented by Gruner, 19) the Fe^{++}/Mg ratio is 10.5. This may indicate that the Fe^{++}/Mg ratio in minnesotaite is variable and that a complete or partly completed solid-solution series exists between minnesotaite and talc. In the analyses presented in this paper (A, B, C, D, E, Table 2) the calculated Fe^{++}/Mg ratio in minnesotaite ranges from 3.0 to 5.5. How closely this calculated ratio agrees with the actual ratio is not known.

In the rocks of the Gogebic district, the minnesotaite occurs as colorless to pale green or yellowish needles or flakes that commonly are arranged as rosettes. Often there is a slightly noticeable pleochroism with Z and Y = pale green, X = pale yellow or colorless. Indices measured on a sample in the present study (Table 5) are similar to those determined by Gruner (19) and by Flaschen and Osborn (11).

TABLE 5

OPTICAL INDICES FOR MINNESOTAITE

	N_x	$N_y \simeq N_z$
Gruner (19)	1.580	1.615
Flaschen and Osborn (11)	1.586	1.618
This study	1.585	1.616

Stilpnomelane is present in much of the silicate-rich iron-formation, typically as a minor mineral associated with minnesotaite. Like minnesotaite, stilpnomelane occurs as plates or needles, and though it has a darker color, higher birefringence, and stronger pleochroism, the two minerals are often difficult to differentiate in very fine-grained rocks. The optical properties of stilpnomelane vary greatly with the ratio of iron to magnesium and of ferrous iron to ferric iron (25).

Greenalite was not identified in the present study although it was previously reported as being present in subordinate amounts by Van Hise and Leith (48, p. 231).

Chlorite is an important constituent only in iron-formation in which there is evidence of some clastic material. The chlorite has not been specifically identified, but James (27, p. 256) has recognized the variety aphrosiderite and possibly thuringite in the Iron River district and Mann (37, p. 261) has identified aphrosiderite in the Ironwood iron-formation. The alumina content of parts of the iron-formation containing appreciable chlorite is typically much higher than in the rest of the formation.

Although greenalite has generally been accepted as being of primary origin (16, 44, 28, 49) there is some doubt as to the primary origin of minnesotaite and stilpnomelane. Gruner (20, p. 12) considers minnesotaite and stilpnomelane to be original constituents of the iron-formation and suggests that they crystallized from a colloidal gel. White (49, p. 37), after careful consideration of the mineralogical relationships of the Biwabik iron-formation, con-

cludes that most of the minnesotaite and stilpnomelane in the Biwabik is of primary origin, largely formed during the diagenetic period.

James (28, p. 266–267) cites evidence to suggest that minnesotaite and stilpnomelane may be derived by metamorphism from pre-existing silicate material of similar composition (such as greenalite) but also notes (29, p. 1462) that minnesotaite and stilpnomelane are characteristic of silicate-rich iron-formation that has undergone only very low grade regional metamorphism. Tyler (44), Tyler and Twenhofel (46), and Mann (37) regard all minnesotaite and stilpnomelane as being metamorphic in origin. Tyler (44, p. 1105) notes that " . . . greenalite which contains about 39 percent iron may be observed in thin sections in all stages of alteration to minnesotaite."

Flaschen and Osborn (11) discuss the phase equilibrium relationships between greenalite, minnesotaite, fayalite, magnetite, and quartz at various temperatures and partial oxygen pressures in the system FeO-Fe_3O_4-SiO_2-H_2O. Their work indicates that stable assemblages in this system at temperatures up to 250° C include greenalite-minnesotaite-water and minnesotaite-quartz-water, in both cases with or without magnetite. Stilpnomelane can form along with or in place of minnesotaite if the necessary alumina is available. Fayalite is not stable below 250° C in the presence of an aqueous phase and so probably can be eliminated from consideration as a primary sedimentary iron-silicate mineral. The particular assemblage present is determined by the ratio of iron to silica and of ferric to ferrous iron.

The point being emphasized here is that although it is not possible to state definitely that the minnesotaite and stilpnomelane of the Ironwood iron-formation are primary minerals in the strict sense of the term, their origin, if attributed to alteration of greenalite or other pre-existing iron-silicate material, probably lies somewhere in the hazy zone between diagenetic processes operating at earth surface temperatures (here considered part of the primary environment) and more truly metamorphic processes operating at somewhat higher but not extreme temperatures.

The lines of evidence cited by White (49, p. 35–38) as opposing the contact metamorphic origin of the major portion of the iron silicates in the Biwabik iron-formation apply equally well to the Ironwood iron-formation. Most notable of these are the stratigraphically controlled distribution of the iron-silicates and the lack of correlation with local metamorphic effects due to dikes or veins.

Magnetite-rich Rocks.—Several varieties of magnetite-rich rocks are found in the Ironwood iron-formation. The most common of these makes up much of what has been called "wavy-bedded" iron-formation by Hotchkiss (22) and Aldrich (1), and is the dominant rock type of the Plymouth and Norrie members. This rock type corresponds in all respects to the "irregularly banded taconite" as described from the Mesabi Range by Gruner (20) and White (49).

Typically this rock is made up of irregular beds and lenses of chert separated by lamina of dark material that consists dominantly of magnetite, carbonate, and silicates. The cherty layers range in thickness from a fraction of an inch to several inches and are on the average somewhat thicker than the

interbedded "slaty" layers. The cherty layers pinch and swell, commonly terminating rather abruptly; the "slaty" layers are generally finely laminated and of more constant thickness.

The chert is dark gray to red in color. The red chert typically is granular or oolitic. Some of the ooliths are made up of concentrically arranged hematite and chert and the good preservation of the concentric structure suggests a primary origin for the hematite. Fine clastic(?) quartz grains form nuclei for some of the ooliths. Granules or ooliths composed dominantly of chert are either structureless (granules) or contain ghost-like rings of dusty hematite, magnetite, or other material. In ooliths or granules in which magnetite is dominant, the coarse-grained and euhedral character of the magnetite suggests replacement of hematite in the oolith. Silicate granules or interstitial silicate material is present in many of these cherts. The carbonate occurs both as scattered grains showing rhombic outline and as fine-grained interstitial material.

The "slaty" material that separates the granular cherty beds and lenses is composed dominantly of magnetite, carbonate, and silicates, with interstitial chert. The magnetite is generally euhedral; it occurs both as disseminated material and clustered in preferred layers. The other minerals also show some preferential layering. In many thin sections probable granule structure may be observed in the silicate material, although the outlines are obscure; stilpnomelane is slightly dominant over minnesotaite in this rock type.

Some magnetite-rich rock is evenly bedded, commonly with magnetite in layers up to half an inch thick interbedded with impure layers of silicate, carbonate, and chert. Carbonate is the most important accessory in the magnetite layers although some silicate is commonly present.

Another even-bedded, magnetite-rich variety consists of interbedded chert and magnetite with little or no silicates or carbonate. Commonly the chert is a brilliant red jasper that is in striking contrast to the black magnetite layers. Most of the jasper layers are non-oolitic; the hematite that is the coloring matter occurs as a fine dust scattered throughout the chert. The jasper layers may fray out laterally into magnetite-rich layers. Chert layers that are oolitic are more irregular in thickness than the non-oolitic type. The ooliths contain hematite with well-preserved concentric structures, but commonly the hematite is nearly or completely replaced by coarse euhedral magnetite or carbonate or silicate. James (28, p. 262) has interpreted this as indicating at least partial instability of the primary hematite in the diagenetic environment with the resultant alteration to ferrous compounds.

A chemical analysis of the jasper-magnetite type of iron-formation is given in Table 6. As with the other iron-formation analyses presented in this paper, this analysis represents the average for several feet of stratigraphic section and does not reflect the vastly different character of individual beds. The approximate mineralogical composition of the analyzed material is given in Table 7. FeO and MgO have been partitioned according to the procedure described in the section on the carbonate-rich rocks. All Fe_2O_3 was assigned to magnetite, but the relatively low iron content calculated for the carbonate

TABLE 6

CHEMICAL ANALYSIS OF JASPER-MAGNETITE IRON-FORMATION
Analyst: Lucile N. Tarrant, U. S. Geological Survey

SiO_2	34.44
Al_2O_3	0.85
Fe_2O_3	30.54
FeO	22.06
MgO	2.30
CaO	1.72
Na_2O	0.00
K_2O	0.13
H_2O^-	0.17
H_2O^+	0.44
TiO_2	0.02
CO_2	7.36
P_2O_5	0.07
S	0.01
MnO	0.21
C	0.04
Total	100.36
Less O for S	0.01
	100.35

Locality: (HJ-97-52; Lab. No. 52-1592). Drill hole No. 1201, 499 to 510 feet, SE¼SE¼ sec. 12, T. 47 N., R. 45 W., Gogebic County, Michigan.

suggests that some allowance should be made for hematite with a resulting slight decrease in magnetite percentage and increase in carbonate and silicate percentages. Magnetite and chert are by far the dominant minerals with carbonate and silicate as important constituents.

Hematite-rich Rocks.—Hematite-rich iron-formation, although of local importance in some of the Lake Superior districts, is rare as a primary rock type on the Gogebic Range. The wavy-bedded iron-formation previously described often contains appreciable hematite, but magnetite generally is the dominant iron oxide.

Pyrite-rich Rocks.—Pyrite-rich rocks are of minor importance in the Ironwood iron-formation and are represented by pyritic carbonaceous slates. These slates are black, fine-grained, and have a well-developed parting parallel to the bedding. The pyrite is generally concentrated in discrete layers. Some later mobility of the pyrite is indicated by a few cross-cutting veinlets but the restriction of the pyrite to specific stratigraphic units attests to its primary or diagenetic origin.

TABLE 7

APPROXIMATE MINERALOGICAL COMPOSITION, IN WEIGHT PERCENT, OF JASPER-MAGNETITE IRON-FORMATION AS CALCULATED FROM ANALYSIS IN TABLE 6

Magnetite	44.3
Quartz	31.3
Carbonate	17.5
Silicate[1]	6.0
Excess constituents[2]	1.3
	100.4

[1] Calculated as minnesotaite.
[2] Includes Al_2O_3, K_2O, P_2O_5, and minor elements.

The pyrite occurs as irregular blebs or aggregates of fine-grained material in which individual crystal outlines are not generally discernible; the matrix consists of chert, chlorite, and carbonate, with minor carbonaceous material. The non-pyritic beds consist of an intimate mixture of chert, carbonate, chlorite, and undetermined argillaceous and carbonaceous material. Quartz is present also as scattered very fine clastic grains.

A chemical analysis of pyritic slate is presented in Table 8. The analysis shows a pyrite content of approximately 3.6 percent, but the analyzed sample represents about 12 feet of stratigraphic section and as the pyrite is not uniformly distributed, some layers of the rock contain much more than the above percentage.

TABLE 8

CHEMICAL ANALYSIS OF PYRITIC SLATE
Analyst: Lucille M. Kehl, U. S. Geological Survey

SiO_2	51.81
Al_2O_3	6.78
Fe_2O_3	3.44
FeO	19.83*
MgO	3.46
CaO	0.37
Na_2O	0.00
K_2O	0.00
H_2O^-	0.33
H_2O^+	4.32
TiO_2	0.93
CO_2	4.30
P_2O_5	0.16
S	1.94
V_2O_3	0.04
MnO	0.49
C	2.54
Total	100.74
Less O for S	0.49
	100.25

* The acids used to dissolve the sample do not attack pyrite. Therefore, a calculated correction, based on the sulfur present, was made on the FeO to take care of the Fe in the pyrite. In making this correction it was assumed that all sulfur is present as pyrite.

Locality: Drill hole No. 121, 715 to 736 feet, SE¼SE¼ sec. 31, T. 47 N., R. 2 E., Iron County, Wisconsin.

The sample contains 2.54 percent carbon. X-ray study of similar material from the Iron River district has shown that the free carbon occurs as "poorly crystalline carbon" rather than as true graphite (28, p. 251). In areas of higher metamorphic grade, true graphite may be present (29).

Carbonate content is about 10 percent, but the calculation of molecular composition is inexact because of the uncertainty of the mineralogical distribution of FeO, MgO, CaO, and MnO in this rock type.

Miscellaneous Rock Types.—The so-called "sweepings bed," which occurs at the base of the iron-formation, is a transition phase between the iron-formation and the underlying Palms quartzite. It marks the beginning of the period of chemical sedimentation, typified by the iron-formation, with the gradual exclusion of clastic material.

The "sweepings bed" is commonly several feet thick and rarely is as much as ten feet thick. The lower part is a quartzite with a chert matrix. The percentage of clastic quartz decreases upward in the unit so that near the top it consists of chert with only scattered quartz grains. The chert is granular and oolitic, commonly reddish, and similar to the cherts described elsewhere in this paper.

TABLE 9

CHEMICAL ANALYSES OF ARGILLITE FROM IRON-FORMATION AND AVERAGE COMPOSITION OF PRECAMBRIAN LUTITES

	A	B	C Average Precambrian lutite
SiO_2	56.64	55.73	58.32
Al_2O_3	10.18	14.82	18.44
Fe_2O_3	4.66	1.37	3.75
FeO	16.07	14.21	4.13
MgO	4.09	4.17	2.21
CaO	0.19	0.04	0.78
Na_2O	0.04	0.06	0.96
K_2O	1.97	3.38	4.42
H_2O^-	0.19	0.11	0.43
H_2O^+	5.39	5.22	3.43
TiO_2	0.47	0.53	0.78
CO_2	0.00	0.00	0.74
P_2O_5	0.09	0.04	0.13
S	0.01	0.12	0.03
V_2O_3	0.01	0.01	trace
MnO	0.03	0.06	0.08
C	0.00	0.46	0.69
SO_3			0.14
FeS_2			0.54
Total	100.03	100.33	100.00
Less O for S	0.01	0.06	
	100.02	100.27	

A. Argillite (NKH-102-53; Lab. No. 53-2105CD). Drill hole No. 131, 352 to 355 feet. Sunday Lake mine, sec. 10, T. 47 N., R. 45 W., Gogebic County, Michigan. Analyst: Lucille M. Kehl, U. S. Geological Survey.

B. Argillite (NKH-101-53; Lab. No. 53-2104CD). Drill hole No. 1201, 1,461 to 1,482 feet, Vicar exploration, SE¼SE¼ sec. 12, T. 47 N., R. 45 W., Gogebic County, Michigan. Analyst: Lucille M. Kehl, U. S. Geological Survey.

C. Weighted average of 36 analyses of Precambrian lutites from the Lake Superior region (39, p. 57).

Fragmental or conglomeratic rock zones occur at many places within the iron-formation. The principal occurrences of breccia or conglomerate are at the base of the Plymouth member, near the top of the Plymouth member, and at the base of the Pence member (22, 1). The latter, which is the most persistent, is known in the district as the "Middle Conglomerate." These zones have been interpreted by Hotchkiss (22) as indicating disconformities within the iron-formation sequence. Fragmental zones are not confined to specific horizons, however, and can be found at many places throughout the section.

The fragments in the breccias are composed entirely of iron-formation, and

most fragments are similar to the rocks of the underlying strata. The angularity of most fragments indicates that the eroded or disturbed material was at least partly indurated and the distance of transportation small. The matrix of the rock consists of chert, hematite, siderite, silicate and magnetite in various combinations. The chert is commonly reddish, with granular or oolitic structure. The evidence suggests that most of the fragmental zones represent periods of strong wave or current action on the bottom rather than extensive erosion and redeposition. The formation of the "Middle Conglomerate" and other more widespread zones may call for shallowing of the water with elevation of extensive parts of the depositional basin above the normal wave base.

Argillite, a fine-grained rock of clastic origin as distinguished from the fine-grained, even-bedded "slates" largely of chemical origin, is of importance within the iron-formation only on the eastern end of the range. At the Sunday Lake mine at Wakefield, Michigan, about 100 feet of argillite occurs in the lower part of the iron-formation. Drilling at the Vicar exploration, about 3 miles east of the Sunday Lake mine, indicates about 165 feet of argillite just above the base of the formation.

The argillite is generally finely laminated and dark greenish-gray in color. Most of it possesses good parting parallel to the bedding; locally a true slaty cleavage is developed at an angle to the bedding.

Two chemical analyses of this argillite are given in Table 9. Also included in Table 9 for comparison is an average analysis for Precambrian lutites (mostly of Animikie age) as compiled by Nanz (39, p. 57).

It can readily be seen that the iron content of these argillites is approximately twice that of Nanz's average. With the exception of two Keweenawan samples, the only other samples among the 36 analyses listed by Nanz (39, p. 53–54) that approach this iron content are those closely associated with iron-formation, such as the "footwall" and "hangingwall" strata of the Iron River district and a "magnetic clay slate" from the base of the Tyler formation.

The complete absence of carbonate is notable when compared with the presence of this material in all the iron-formation analyses presented in previous sections of this paper.

In thin section the argillite is seen to consist largely of fine-grained clastic quartz, chlorite, and sericite with lesser feldspar (plagioclase and minor K-feldspar), magnetite, and carbonaceous material. Some minnesotaite appears to be present but it is difficult to estimate its abundance because of the presence of appreciable sericite. Occasional beds of coarser fragmental material and of granular chert are present within the argillite. Carbonate apparently does not occur as a primary constituent although minor vein carbonate can be seen in some specimens.

Distribution of Rock Types

Granular, cherty, magnetite-rich rock makes up most of the irregular-bedded iron-formation typical of the Plymouth, Norrie, and Anvil members. This rock locally grades into material in which carbonate, silicate, or hematite

TABLE 10

GENERALIZED STRATIGRAPHIC DESCRIPTION OF IRON-FORMATION FROM DRILL HOLE NO. 121, PENCE, WISCONSIN

D.D.H. No. 121, SE¼SE¼ sec. 31, T. 46 N., R. 2 E., Wisconsin. This hole was drilled from the surface just northwest of the town of Pence and encountered the Pabst member of the Tyler formation (Atwater, 4) at the bedrock surface. Approximate stratigraphic thicknesses are given.

Pabst member of Tyler formation:

5.5 ft. (Core lost[1]) Conglomerate. Red and gray chert pebbles in a matrix of granular chert. Some layers of even-bedded carbonate-rich rock.
11 ft. (Core lost) Even-bedded chert-carbonate rock.
2.5 ft. Conglomerate with fragments of red and gray chert in a granular chert matrix. Minor magnetite and carbonate present; partly oxidized.

Ironwood iron-formation:

Anvil member:

17 ft. Even-bedded chert-carbonate rock with considerable magnetite. In some layers carbonate is minor and magnetite is dominant iron mineral; partly oxidized.
25 ft. (Core lost) Even-bedded chert-carbonate rock with considerable magnetite.
11 ft. (Core lost) Even-bedded chert-carbonate rock with some dense flinty chert layers and irregular layers of granular chert.
53 ft. Total thickness Anvil member.

Note: In this part of the range much of the Anvil has been removed by erosion prior to the deposition of the Pabst (4, p. 163).

Pence member:

26 ft. (Core lost) Even-bedded chert-carbonate rock with minor magnetite; partly oxidized.
61 ft. Even-bedded chert-carbonate-silicate rock with considerable magnetite. The chert occurs chiefly as interstitial material although scattered layers of granular chert are present. Carbonate is generally dominant over silicate although the ratio varies greatly from layer to layer. Magnetite occurs disseminated throughout individual layers but varies greatly in percentage from layer to layer. Carbonaceous material is commonly present as thin irregular laminae. Analysis B, Table 2, gives the average chemical composition of about 6.5 feet of the lower part of this section and Table 3 gives the approximate mineralogical composition.
15.5 ft. (Core lost) Even-bedded chert-carbonate rock with occasional beds of conglomeratic, granular chert.
14 ft. Even-bedded chert-carbonate-silicate rock similar to above.
6.5 ft. Conglomerate. Angular fragments of green to gray chert in a granular and oolitic chert matrix. Also contains fragments of what appears to have been partly indurated even-bedded material.
122 ft. Total thickness Pence member.

Norrie member:

117 ft. Wavy-bedded granular-cherty rock. The entire Norrie has been extensively oxidized and the iron occurs mostly as soft red hematite. Core recovery is poor except for scattered pieces of chert. Chert shows relict granule structures.

Yale member:

15 ft. Even-bedded chert-carbonate rock with minor silicate and magnetite; partly oxidized.
6.5 ft. Wavy-bedded granular chert, somewhat conglomeratic. Oxidized.
34 ft. Even-bedded chert-carbonate rock with minor silicate and magnetite. Rock is similar to much of the Pence above except for greater percentage of carbonate and smaller percentage of silicate and magnetite. The chert occurs both as disseminated material in the carbonate-rich layers and as thin beds, commonly irregular or nodular. Carbonaceous material is present along stylolite seams, both within carbonate layers and at the contact

[1] The notation "core lost" indicates that for a particular section of drilling the core has been lost or misplaced and was therefore unavailable for re-examination. For those sections, descriptive information was obtained from core logs written by Theodore Roy and used with the permission of the Republic Steel Corporation.

TABLE 10—(*Continued*)

GENERALIZED STRATIGRAPHIC DESCRIPTION OF IRON-FORMATION FROM DRILL HOLE NO. 121, PENCE, WISCONSIN

between carbonate and chert layers. The stylolite seams range in size from microscopic structures with extremely small amplitude to megascopic structures with an amplitude of several millimeters. Analysis C, Table 2, gives the average chemical composition of about 7.5 feet of the carbonate rock type, located about 5.5 feet from the top of this section. Table 3 gives the approximate mineralogical composition.

12 ft. Finely laminated black carbonaceous, pyritic slate. The average chemical composition of this rock is given in Table 8.
67.5 ft. Total thickness Yale member.

Plymouth member:

100 ft. Wavy-bedded granular-cherty rock. The entire Plymouth has been extensively oxidized and the iron occurs largely as soft red hematite. Core recovery poor except for pieces of granular chert. Chert layers occasionally conglomeratic.
48 ft. (Core lost) Similar to above.
6 ft. (Core lost) "Sweepings bed." Conglomeratic and granular chert with clastic quartz.
154 ft. Total thickness Plymouth member.
513.5 ft. Total thickness Ironwood iron-formation.

Palms quartzite:

Quartzite.

predominates among the iron minerals. The irregular-bedded parts of the Yale and Pence members are similar.

Carbonate and silicate rocks make up the greater part of the even-bedded iron-formation. These rocks intergrade both vertically and laterally, and may be interbedded with or gradational into even-bedded magnetite-silicate rocks. Chert-magnetite and jasper-magnetite rocks occur most commonly in the upper part of the Pence member and are especially well developed on the eastern end of the range. Even-bedded, pyritic, carbonaceous rock is found only in the Yale member, generally in the lower part.

As examples of the distribution of rock types in the iron-formation, descriptions are presented of the rocks penetrated in two drill holes just west of the town of Pence, Wisconsin. Parts of the formation in this area have been extensively oxidized, with resultant mineral alteration and destruction of primary textures, but many sections of the core show only minor alteration and serve as excellent examples of various rock types occurring in the iron-formation (Tables 10 and 11).

On the generalized cross section (Fig. 6) corrections have been made for the angle between the bedding planes and the direction of penetration, but the stratigraphic thicknesses indicated are only approximate.

The stratigraphic descriptions show that the granular-cherty rocks in this area have been extensively oxidized here as they have been throughout the remainder of the range to the east. The fact that this rock type is more susceptible to oxidation than the even-bedded types of iron-formation has been noted previously by Hotchkiss (22, p. 579) and by Aldrich (1, p. 140). A specimen of virtually unoxidized, irregular-bedded, granular-cherty rock was obtained from drilling at the Atlantic property, about one mile west of the described holes near Pence. This rock, as described in the section on magnetite-rich rocks, consists of irregular beds of granular chert separated by

TABLE 11

GENERALIZED STRATIGRAPHIC DESCRIPTION OF IRON-FORMATION FROM DRILL HOLE NO. 113, PENCE, WISCONSIN

D.D.H. No. 113, NW¼NE¼ sec. 6, T. 45 N., R. 2 E., Wisconsin. This hole was drilled from the surface just west of the town of Pence and encountered the Tyler formation (Atwater, 4) at the bedrock surface. Approximate stratigraphic thicknesses are given.

Tyler formation:

11 ft. Black magnetic slate and dark green even-bedded rock containing carbonate, chlorite, magnetite, and minor quartz.

Pabst member of Tyler formation:

11.5 ft. Conglomerate with angular jasper and chert fragments in a granular chert matrix. Minor zones of even-bedded chert-carbonate rock.
8 ft. Even-bedded carbonate-silicate-magnetite rock similar to even-bedded rock in Tyler above and in iron-formation below.
10.5 ft. Conglomerate. Jasper and chert pebbles in matrix of granular and oolitic chert. Considerable magnetite.

30 ft. Total thickness Pabst member.

Ironwood iron-formation:

Anvil member:

8 ft. Even-bedded carbonate-silicate rock with considerable magnetite. Carbonate, silicate, and magnetite percentages vary greatly from layer to layer. Silicate material largely chlorite.
14.5 ft. Wavy-bedded granular-cherty rock. This section is extensively oxidized and the iron occurs largely as soft red hematite.

22.5 ft. Total thickness Anvil member.

Note: In this part of the range much of the Anvil has been removed by erosion prior to the deposition of the Pabst (4, p. 163).

Pence member:

27.5 ft. Even-bedded chert-carbonate rock with considerable silicate and magnetite. Numerous thin layers of irregular-bedded, granular chert.
74.5 ft. Even-bedded chert-hematite rock, extensively oxidized.

102 ft. Total thickness Pence member.

Norrie member:

115 ft. Wavy-bedded granular-cherty rock. Entire Norrie extensively oxidized. Iron occurs as soft red hematite. Core recovery poor except for scattered pieces of chert. Chert shows relict granule structures.

Yale member:

35.5 ft. Even-bedded chert-carbonate rock with minor silicate and magnetite. Chert in dark flinty layers and as disseminated material. Few granular chert zones present. Minor carbonaceous material present. Carbonate and silicate material partly oxidized.
13 ft. Finely laminated black carbonaceous, pyritic slate.

48.5 ft. Total thickness Yale member.

Plymouth member:

125 ft. Wavy bedded granular-cherty rock. Entire Plymouth extensively oxidized as is Norrie above. Iron occurs largely as soft red hematite. Chert has relict granule structures as evidenced by distribution of powdery hematite and by differences in grain size of the crystallized chert (quartz).
3 ft. Thinly and evenly bedded hematitic rock, well oxidized.
5 ft. "Sweepings bed." Conglomeratic and granular chert and jasper with clastic quartz grains near base.

133 ft. Total thickness Plymouth member.
421 ft. Total thickness Ironwood iron-formation.

Palms quartzite:
Quartzite.

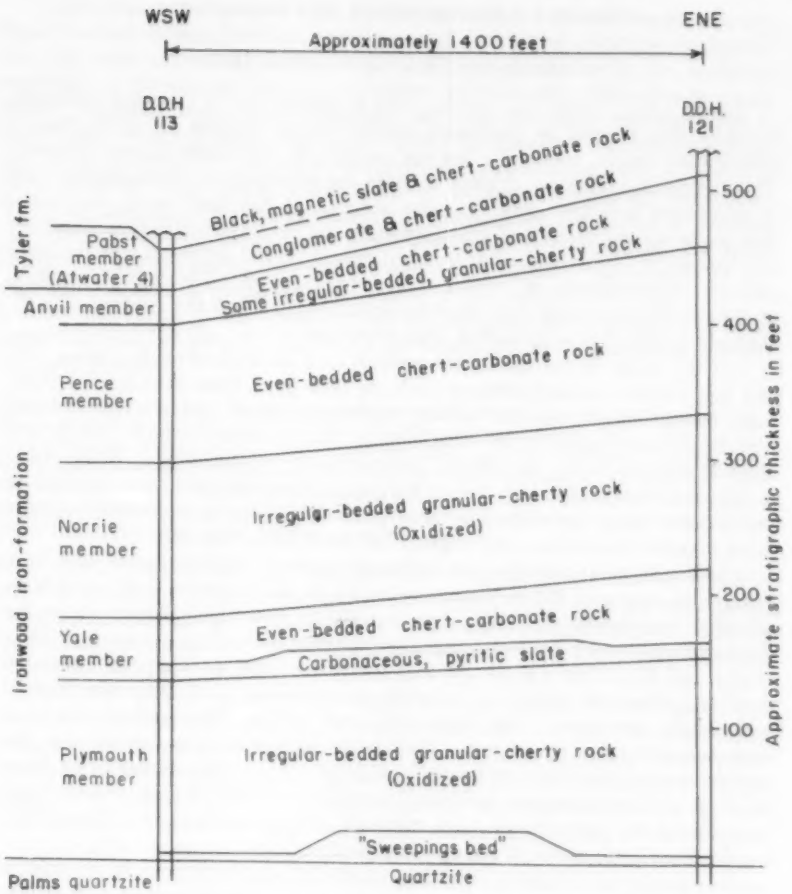

FIG. 6. Generalized stratigraphic section of Ironwood iron-formation near Pence, Wisconsin.

laminae of carbonate-silicate material. Considerable magnetite is present, both in the granular chert and in the carbonate, silicate laminae.

An example of lateral gradation of rock types is also present in the Pence area. The Pence member as described in Tables 10 and 11 (drill holes No. 113 and No. 121) consists largely of even-bedded chert-carbonate rock. About 1 mile to the east of these holes the Pence member is represented by an even-bedded chert-magnetite rock with considerable jasper and minor silicate material. Unfortunately, information concerning the details of gradation in the intervening area is lacking.

ORIGIN OF THE IRONWOOD IRON-FORMATION

Sedimentary Facies of Iron-formation

James (28, p. 239) has defined iron-formation as "a chemical sediment, typically thin-bedded or laminated, containing 15 percent or more iron of sedimentary origin, commonly but not necessarily containing layers of chert." This definition makes no attempt to state the chemical or mineralogical form in which the iron and other material occurs. It has been noted that rocks that make up the Ironwood iron-formation are of widely differing character and that these differences must to some extent reflect differences in the sedimentary environments in which they were formed. Through recognition of these differences and their environmental implications the concept of sedimentary facies of iron-formation was developed.

On the basis of the dominant original iron mineral present, James (27, 28) has divided the sedimentary rocks of iron-formations into several lithologic facies. These are the sulfide, carbonate, oxide (both magnetite and hematite), and silicate facies. Each facies has its own chemical and mineralogical characteristics as well as environmental implications. White (49) in his recent description of the rock types of the Biwabik iron-formation of the Mesabi Range develops the same general classification although using a more detailed breakdown and slightly different nomenclature.

Until relatively recently, the carbonate type of iron-formation had been thought to represent the only primary facies in the Ironwood iron-formation; all other iron-formation rocks were thought to have been derived from the chert-carbonate rock by metamorphism or other secondary processes. Thus Irving and Van Hise (26, p. 247) in the first major work on the Ironwood iron-formation state that " . . . the cherty carbonates . . . were the original rocks of the member." Van Hise and Leith (48, p. 231) reaffirm this view with respect to the Ironwood: "The cherty iron-bearing carbonate was the original rock of the iron-formation." Aldrich (1, p. 136) states: "The Ironwood, in its original states, comprised two distinct types of rock. Both types were chemically precipitated silica minerals and iron carbonate. They differ compositionally in ratio of silica to carbonate . . . ."

One of the few exceptions to this viewpoint was expressed by Hotchkiss (22, p. 446) who suggested that when the wavy-bedded iron-formation was precipitated the water was shallow enough and contained enough oxygen for iron to be precipitated as the oxide.

Although there is little doubt as to the primary nature of most of the carbonate present in the iron-formation and as to the importance of carbonate iron-formation as a primary facies of the Ironwood, the diversity of rock types in the relatively unaltered iron-formation indicates that other primary facies are also of importance.

Environmental Implications of Facies Concept.—James (28) and White (49) have discussed the principal features and origin of the various facies of iron-formation and only a brief summary of some of the environmental implications of the facies concept will be given here.

Numerous recent papers (32, 24, 23) have noted that different primary iron minerals reflect different environmental conditions and have suggested that the chief controlling factor involved in their formation is the oxidation potential of the depositional or diagenetic environment. Hematite is stable under oxidizing conditions, magnetite and siderite under intermediate to moderately reducing conditions, pyrite under moderately reducing conditions, and iron sulfide (FeS) under strongly reducing conditions (23). Iron silicates probably form under intermediate to moderately reducing conditions. The main factors controlling the oxidation potential are the degree of aeration and the presence of organic material. The latter is reflected by the large amount of carbonaceous material present in the pyritic slates and by the common presence of carbonaceous material in the carbonate rocks.

Hotchkiss (22, p. 446) was the first to recognize the implication of these environmental factors with respect to the origin of the Ironwood iron-formation and stated:

> . . . it is believed that the wavy-bedded members of the iron formation are relatively shallow water deposits in which the bottom was within reach of the action of waves that disturbed the bottom and produced the wavy-bedded structure, and the water contained abundant oxygen to oxidize the iron as it was deposited. The even-bedded portions of the formation are believed to have been deposited in deeper water where the bottom was below the reach of wave action and contained so little oxygen that the iron could persist as carbonate.

In support of this belief is the fact that the irregular-bedded cherts typically show granular or oolitic structures that suggest shallow water conditions. What Hotchkiss did not recognize was that under intermediate or reducing conditions, magnetite, iron silicates, and pyrite might form as primary minerals as well as siderite.

Complete separation of the physical-chemical aspects of the depositional and the diagenetic environments is not possible. One of the few generalizations that can be made is that in fine-grained sediments the oxidation potential generally decreases with depth (52, p. 503; 10, p. 773). Shepard and Moore (42, p. 1589) have indicated exceptions to this generalization, however, and such things as content of organic material and water content probably have a notable effect upon the oxidation potential of the burial environment.

James (28, p. 275) has pointed out that the modifications of iron-formation that might be attributed to diagenesis typically reflect a lowering of the oxidation potential with burial. These include the replacement of hematite ooliths by magnetite, some replacement of primary oxides and silicate by carbonate, and replacement of carbonate by pyrite. All are features that may be observed in the rocks of the Ironwood iron-formation.

Relation of Chemical Environments to Physical Parameters.—The various chemical environments that determine the form in which the iron is deposited are in turn determined by various physical parameters such as shape and bottom configuration of the basin, depth of water, nearness to shore, degree of circulation, content of organic material, and so on. The effects of some of these parameters are reflected in the sedimentary structures retained in the rocks and others may be deduced from the supposed primary mineralogy.

Granules and ooliths, numerous intraformational conglomerates, and other shallow-water structures throughout the iron-formation suggest shallow-water deposition for at least a large part of the iron-formation. Restricted conditions and lack of aeration are suggested by the parts of the iron-formation requiring low oxidation potentials for their development, although rapid burial with included organic material might also provide these conditions. Elongate basins marginal to a land mass of low relief (28, p. 279) or a shallow, relatively tideless, epicontinental sea (49, p. 52) seem best to fit these requirements. Tyler and Twenhofel (46), James (28), and White (49) have all pointed out that vastly different chemical as well as clastic sediments may be deposited simultaneously in a single depositional basin or shelf area. The type of sediment that is deposited at any locality is determined by various factors, of which the most important is probably the distance from shore with its resultant effect upon water depth, aeration, and removal of clastic material.

In his analysis of the sedimentary environment in which the Biwabik iron-formation was deposited, White (49, p. 45) states that "the contemporaneous deposits being formed, in order of increasing distance from shore, were (1) clean sand; (2) silt and clay (missing at many places); (3) lean chert with algal structures; (4) hematitic rocks; (5) minor chert-siderite rocks; (6) chert and magnetite, with more iron silicates seaward; and (7) iron silicates with some siderite." With the superposition of a transgressing (or regressing) shore line upon this sequence of differing environments, a stratigraphic sequence of lithic units will be built up that will not be time parallel in a section perpendicular to the shore line. Parallel to the shore line the lithic units will be more nearly time parallel but some lateral lithologic gradation may result from local environmental differences. As noted by White (49, p. 41) "The aspect of sediments formed simultaneously at a given distance from shore . . . is characterized by an over-all uniformity, which at most places outweighs the changes produced by lateral gradation." Repetition of similar strata would indicate a series of transgressions and regressions.

In the main part of the Mesabi Range, the iron-formation stratigraphy is relatively uniform throughout the present outcrop belt. White (49, p. 47) interprets this as an indication that the present exposure of the range is roughly parallel to the old shore line. He assumes that the closest shore line was to the north of the range because of correlation of rocks of the Animikie group (which includes the Biwabik iron-formation) to the south in the Emily district. The increased proportion of argillite and its intertonguing relationship with non-clastic iron-formation on the western Mesabi has been interpreted by White (49, p. 43) as indicating a southward bend in the shore line, across the present trend of the main part of the range.

Marine Versus Nonmarine Environment

In the development of the Eh-pH environmental diagram (32, 24, 23) it was assumed that the iron minerals were deposited under "normal" marine

conditions. It was realized that conditions may vary appreciably from the assumed "normal," especially in regard to ionic concentrations existing under conditions of restricted circulation. "Normal" marine concentrations only entered into the calculations involving sulfide equilibria, however, as the carbonate system was assumed to be in equilibrium with the partial pressure of carbon dioxide in the atmosphere, which presumably would be the same regardless of the nature of the aqueous sedimentary environment. It is possible that the carbon dioxide content of the Precambrian atmosphere was somewhat different than at present, but the work of Rubey (40) suggests that radical changes in the atmosphere during recorded geologic time are not supported by the geologic evidence.

Tyler and Twenhofel (46, p. 137) believe that "the iron and silica deposits are of fresh water and not of marine origin." Their chief argument is based upon the relatively low percentage of calcium and magnesium present in the carbonate of the iron-formations. As noted by both James (28, p. 243, 253–255) and White (49, p. 49), however, and as shown by the carbonate compositions presented in this paper, the amount of calcium and magnesium contained in the iron-formation is far from insignificant. It is possible that the high iron content merely "masks" the other ions in the carbonate, as might be expected during a period of iron-rich sedimentation. Further evidence in favor of a marine origin for the iron-formations is presented by James (28, p. 243–244), including the fact that the iron-formations occur within a typically marine sequence.

Origin of the Chert

Chert is one of the dominant minerals of all facies of iron-formation and occurs both as individual beds or lenses and as interstitial material. The chert is now in the form of microcrystalline quartz and ranges in color from white or gray to green, black, or red (jasper) and is commonly granular or oolitic.

It seems fairly well established that the major part of the chert is primary in origin, having been formed as an original constituent of the iron-formation rather than as a later replacement. Two lines of evidence listed by James (28, p. 273) in support of this tenet are the fact that the amount of chert in a given bed of iron-formation remains almost constant over wide areas, and that slump structures, intraformational conglomerates, and other primary sedimentary structures suggest at least partial solidification of the chert prior to the formation of these features. White (49, p. 34) cites similar evidence in regard to the primary nature of the chert in the Biwabik iron-formation of the Mesabi Range and these features are also common in the Ironwood iron-formation. Examples are not rare of stylolites cutting chert or forming the boundary between adjacent chert and carbonate layers. These factors all indicate that chert was present and in such a condition as to be able to take part in the formation of various primary sedimentary structures, and therefore must in a large part be considered of primary origin itself.

Source of the Iron and Silica

In the discussion regarding the deposition of the iron-rich sediments, a source of iron and silica was assumed but not specifically identified. Aldrich (1, p. 143), in his study of the Ironwood iron-formation discounts the adequacy of surficial weathering as a source for the iron and the silica and states that " . . . these materials (iron and silica) were created in solution by a subsurface environment, a magma." He thus follows the lead of Van Hise and Leith (48, p. 516) who, however, suggested that some of the iron might have been derived by subaerial weathering.

The only volcanism associated with the Ironwood iron-formation is that which produced the greenstone extrusives that reportedly occur within the upper part of the iron-formation at the eastern end of the range (3, p. 48). This volcanism occurred long after iron-rich chemical sedimentation began, however, and the relationship between the volcanism and the iron-formation appears to be spatial or structural rather than genetic.

In a recent analysis of the problem, James (28, p. 277) concludes " . . . that volcanism, though not uncommon during the deposition of the major iron-formations, does not have a close enough correlation in space and time with the iron-rich sediments to be genetically related to those sediments," and " . . . that the relationship between volcanism and iron-formation deposition is structural, not chemical" (28, p. 279). White (49, p. 50) suggests " . . . that volcanism contemporaneous with Animikie sedimentation was detrimental rather than conducive to iron concentration" due to dilution by clastic material of volcanic origin.

James (28, p. 276) points out that " . . . under certain tropical or subtropical conditions the iron and silica content of stream water may be very high and entirely adequate to account for iron-formation deposition." Gruner (15), Gill (12), Moore and Maynard (38), and Sakamoto (41), among others, have reached much the same conclusions. The present writer favors the weathering source over the volcanic source and supports the view that the iron and silica have been derived from a land mass of low relief undergoing deep chemical weathering, probably under humid tropical conditions, and have been transported to the depositional environment partly in solution and partly in colloidal form.

Recent work by Alexander, Heston, and Iler (2); White, Brannock, and Murata (50); and Krauskopf (31) indicates that silica is a great deal more soluble than suggested by the work of Moore and Maynard (38) and others. Krauskopf (31) states that the solubility of amorphous silica ranges from 100 to 140 parts per million in fresh water at 25° C and ranges from 80 to 110 parts per million in sea water at 25° C. Contrary to the conclusions of Correns (7, 8) and others, the new work also indicates that the solubility of silica is independent of pH within the range of normal environments (below pH of 9), and furthermore, that silica in true solution " . . . is not precipitated by the electrolytes of sea water, by other colloids, or by suspended solids like calcite, kaolinite, or montmorillonite" (31). Thus, according to

Krauskopf, although both dissolved and colloidal silica may be expected in natural waters, the former is by far the more common. The transportation of iron in any appreciable amounts, on the other hand, requires a low oxidation potential so as to remain in solution in the ferrous state, or stabilization in the ferric state by protective agents such as organic colloids. Iron and silica in true solution could be separated from clastics near shore and be transported well out into a depositional basin where they would not be precipitated, inorganically at least, until saturation was reached. Upon precipitation, the iron would tend to form minerals in equilibrium with the depositional and diagenetic environments to which it is subjected.

The increase in the known solubility of silica helps to solve the problem of its transportation to the basin of deposition. It does, however, pose new problems regarding the precipitation of silica, as a much higher concentration of silica than hitherto anticipated will be necessary before saturation of the water will occur. Krauskopf (31) believes that the very great undersaturation of the ocean at the present time may be ascribed to the role played by organisms, particularly diatoms, radiolaria, and siliceous sponges. For example, Jørgensen (30) demonstrated that two species of diatoms were able to reduce silica concentrations from initial values of 0.65 to 125 parts per million to the range 0.065 to 0.085 part per million. After the death of the organisms the silica can either return into solution if enough time is available or collect at the bottom. The presence of silica-secreting organisms in Animikie time cannot be demonstrated, unless the algal structures in cherts described by Grout and Broderick (14) Gruner (20), and Tyler and Barghoorn (45) represent this type of an organism. There is no reason to believe that silica secreting or depositing organisms did not exist at that time, however, and the ability of such organisms to remove silica from sea water, even though silica concentration is far below saturation, suggests that their role in the formation of siliceous sediments, such as iron-formation, has been greater than has been generally recognized.

Numerous workers (5, 13, 53, 10) have noted the apparent inability of a natural inorganic system to reduce sulfate to sulfide at ordinary temperatures. Huber (23) noted that for this reason iron sulfide (or pyrite) may fail to form even under conditions where it would be thermodynamically stable and the Eh was low enough to permit reduction of available sulfate. Harder (21) discusses in great detail the role of bacteria in the deposition of other iron minerals and it would appear that organisms are as important in the precipitation of iron as they are of silica.

The present writer has no ready explanation for the alternate layering of iron and silica in the iron-formation. It is suggested, however, that a cyclical variation in the activity of organisms might be a possible explanation. For example, variations in the amount of iron in solution in sea water in the English Channel have been related by Cooper (6) to seasonal variations in the activity of marine plankton. Thompson and Bremner (43) have recorded a reduction in the quantity of iron in sea water coincident with heavy diatom production.

Tectonic Framework of Sedimentation and Depositional History

By the beginning of Animikie sedimentation, the pre-Animikie land mass, composed of greenstone schists and granitic rocks, had been reduced to one of low relief. The Sunday quartzite and Bad River dolomite were deposited in a transgressive sea migrating over this relatively stable, low-lying area. The Sunday quartzite, present only on the eastern end of the range, contains a basal conglomerate and is gradational into the overlying Bad River dolomite. Where the dolomite lies unconformably on the pre-Animikie granites and schists there is commonly a well-developed conglomerate at the contact (22, p. 444). These lithologies represent shelf or shallow basin associations (9). Mild uplift accompanied by regression of the sea caused the major part of the lower Animikie deposits in the present area of the Gogebic district to be removed by erosion.

The Palms quartzite was deposited, still under relatively stable shelf conditions, during a second transgression. The basal part of this formation consists of a conglomerate that contains fragments of the immediately underlying rocks, whether Bad River dolomite or pre-Animikie granite or greenstone. The main part of the formation, the "quartz slate," is generally a thin-bedded rock that ranges in composition from a fairly clean quartzite to feldspathic quartzite and graywacke. The upper 50–75 feet of the formation consists of a highly indurated, clean, vitreous quartzite with cross-bedding and ripple marks. The Palms quartzite, averaging about 450 feet in thickness, is co-extensive with the iron range and rather uniform throughout.

The Palms quartzite grades upward rather abruptly into the Ironwood iron-formation, clastic sedimentation having given way to iron and silica-rich chemical sedimentation. James (28, p. 279) suggests that the advent of chemical sedimentation might coincide with the "critical period" in the development of a geosyncline, the formation of a "low, offshore buckle or swell" with the resultant formation of a restricted basin environment appropriate to chemical sedimentation. Of equal importance, however, is the exclusion of clastic material previously being deposited. If it is assumed that the land mass adjacent to the sea or basin was extremely stable the small amount of clastic material supplied could be effectively removed close to shore. Under such conditions, chemical sedimentation could have begun in deeper water while clastic deposition continued near shore. The relationships between iron-formation and clastic sediments (graphitic argillite and quartz-mica argillite) on the Mesabi Range, as described by White (49), suggests that a series of transgressions and regressions produced an alternating series of lithic units which were time parallel only in a section parallel with the shore line. It is difficult to demonstrate an analogous situation with respect to the Ironwood iron-formation because the field relations between the iron-formation and associated clastic sedimentary rocks, such as the argillite on the eastern end of the range, are not clear.

The alternating lithic units of the Ironwood iron-formation do represent changes in the physical-chemical environment and these may be considered regardless of whether produced by migrating shore lines, or by other fluctua-

tions in basin configurement. In the Pence area, where the most completely known section of the iron-formation has been preserved, the deposition of the Plymouth member began in a rather shallow water environment, as suggested by the granular and oolitic chert and numerous intraformational conglomerates. Deposition of the even-bedded parts of the member suggests, however, that the bottom must have been below wave base at least part of the time. A period of stagnation then ensued with resultant incomplete oxidation of the organic material present; this period is now represented by the carbonaceous, pyritic slates of the lower part of the Yale member. Gradually circulation and aeration increased to the extent that nearly all organic material introduced into the environment was oxidized, the oxidation potential increased somewhat, and the even-bedded, chert-carbonate rocks of the Yale were deposited. That the environment was a fluctuating one is indicated by the minor beds of granular chert that occur in the Yale member. Return of an environment characteristic of the Plymouth is indicated by the irregular bedded granular cherts of the Norrie member.

The chert-carbonate of the Pence member was deposited under conditions similar to those pertaining during the formation of the Yale member. Local differences in environments are indicated by lateral variations in iron-formation members such as the gradation from chert-carbonate to chert-magnetite rock in the Pence member near the town of Pence, Wisconsin.

The depth of water in the depositional basin seems to be extremely critical. The close alternation of irregular and even-bedded material suggests that the depth of water was somewhat greater than "normal" wave base so that only in occasional storms was the bottom disturbed by processes other than ordinary low-angle slumping. The formation of some of the more persistent conglomeratic zones, such as that at the base of the Pence member, suggests more extensive wave action, although still under submarine conditions. The deposition of iron and silica-rich chemical sediments continued under varying environmental conditions until upwards of 500 feet of this material had accumulated.

The relation of the presently exposed part of the Ironwood iron-formation to the shore line of the depositional basin is uncertain. The relative continuity of the five members of the iron-formation on the main part of the Gogebic Range suggests that the shore line was parallel with the present outcrop belt. White (49, p. 49) has suggested that the Gogebic Range might bear "a relation to the southern shore line of the Animikie sea similar to the relation of the Mesabi Range to the northern shore line." If this interpretation is correct, the shore line would have been to the south of the present outcrop belt of the Ironwood iron-formation and the near-shore clastic equivalent of the iron-formation would have been removed by erosion. A major bend in the shore line, swinging northward at the eastern end of the Gogebic Range, would produce a near-shore environment accounting for the argillite associated with the iron-formation and the changes in iron-formation stratigraphy in that area. This northward swing of the shore line would also place a land mass between the Gogebic depositional area and the Marquette area, supporting James' (28, p. 280) view that "dissimilarities in iron-formation

stratigraphy [in the Gogebic and Marquette Ranges] indicate deposition in separate basins."

Increased diastrophism brought to a close the chemical sedimentation typical of the iron-formation and minor and irregular uplift permitted erosion of parts of the iron-formation. With renewed subsidence the later Animikie clastic formations were deposited, beginning with the basal Pabst conglomerate (Copps in the east). At first dominantly composed of iron-formation fragments, this formation shows a gradual increase in clastic quartz and argillaceous material supplied by the newly activated adjacent land mass. In the east part of the district, the Copps conglomerate contains feldspar, mica, and even boulders derived from the pre-Animikie granites of that area (4, p. 172). Chemical sedimentation of iron-rich rocks recurred periodically during the deposition of the Pabst conglomerate and the lower part of the Tyler formation. Ferruginous slates and carbonate with interbedded chert identical to lithologic types within the Ironwood iron-formation are found as much as 800 feet above the base of the Pabst conglomerate (4, p. 162). With increased tectonism chemical sedimentation finally gave way entirely to the deposition of thick graywacke and slate sequencies typical of unstable geosynclinal conditions (9).

U. S. Geological Survey,
Menlo Park, Calif.,
May 14, 1958

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THE ELK RIDGE–WHITE CANYON CHANNEL SYSTEM, SAN JUAN COUNTY, UTAH: ITS EFFECT ON URANIUM DISTRIBUTION[1]

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CONTENTS

	PAGE
Abstract	119
Introduction	120
Elk Ridge-White Canyon channel system	121
Lithology	121
Direction of sediment transport	122
Source of sediments	122
Boundaries and general characteristics	122
Lithologic units	125
Sandstone-mudstone unit	125
Massive sandstone unit	125
Channel scour characteristics	125
Effects of Elk Ridge-White Canyon channel system on distribution of uranium deposits	126
Sandstone-mudstone unit	126
Relation of ore deposits to the margin of the channel system	127
Regional relationships	127
Application of the channel system concept to the search for uranium	128
Acknowledgments	128
References	128

ABSTRACT

Reconnaissance in the White Canyon district, San Juan County, Utah, indicates that rocks of the Shinarump member of the Chinle formation of Triassic age were deposited in that district in two different channel systems; sediments deposited in channels of one system were derived from a source to the east and sediments of the other from a source to the south. The channel system containing sediments derived from the east, the Elk Ridge-White Canyon channel system, was apparently formed by a large braided stream that flowed westward from a source in granitic and metamorphic terrane of the ancestral Uncompahgre highland.

All known uranium deposits of any consequence in the White Canyon district are confined to the Shinarump member deposited in the Elk Ridge-White Canyon channel system. The nature of the channels and the lithologic characteristics of the rocks filling this system of channels combine to form a much more favorable environment for the localization of uranium deposits than do the channels formed and the rocks deposited by northward-flowing streams.

Recognition of channel systems in the White Canyon district suggests that channel systems may be recognized elsewhere in the Shinarump mem-

[1] Publication authorized by the Director, U. S. Geological Survey.

ber, and that the Shinarump member on the Colorado Plateau may be composed of rocks deposited in many coalescing channel systems. In addition, study in the White Canyon district indicates that rocks deposited in some of these channel systems are more favorable hosts for uranium deposits than the rocks deposited in others. Recognition and delineation of these ancient channel systems may be of help in making regional appraisals of ore potential and in the search for new mining districts.

INTRODUCTION

THE area described in this report is part of the White Canyon mining district, San Juan County, Utah (Fig. 1). It extends from Elk Ridge on the east to the Colorado River on the west and includes the Elk Ridge, Deer Flat, White Canyon, Red Canyon, and Red Rock Plateau areas. The exposed rocks are predominantly continental deposits of mudstone, sandstone, and conglomerate and range in age from Permian to Jurassic. Over most of the area structures consist of broad gentle folds, and the beds are nearly flat lying except along the eastern edge of Elk Ridge where dips are as high as 20° to 30° to the east. The area, which lies in the Canyon Lands section of the Colorado Plateau (1), is characterized by mesa and canyon topography, a semiarid climate, and sparse vegetation except on Elk Ridge where aspen

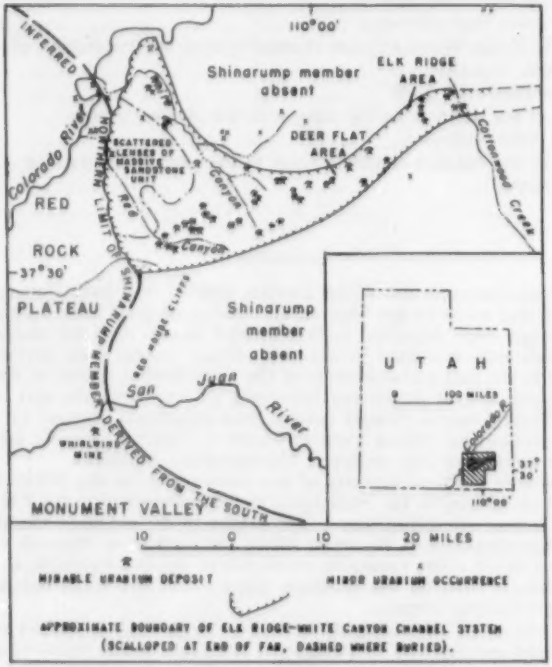

FIG. 1. Map showing boundaries of the Elk Ridge-White Canyon channel system, White Canyon district, San Juan County, Utah.

and yellow pine are locally abundant. The investigation of the area was conducted during 1956 by the U. S. Geological Survey on behalf of the Division of Raw Materials of the U. S. Atomic Energy Commission.

Uranium deposits in the White Canyon district have been described by Miller (8); Trites and Chew (13); Trites, Finnell, and Thaden (14); and Isachsen and Evensen (3). Uranium and copper minerals are associated in tabular elongate ore bodies which are for the most part oriented parallel to bedding and sedimentary trends in fluvial sediments of the Shinarump member of the Chinle formation of Late Triassic age. The ore deposits are from a few inches to 15 feet thick, as much as 300 feet wide, and as much as 3,000 feet long. Near outcrops the ores are oxidized and are characterized by secondary uranium and copper minerals and abundant iron oxides. A few tens of feet away from the outcrop the ores are commonly relatively unoxidized and are composed of uraninite, bornite, chalcopyrite, chalcocite, covellite, pyrite, and very minor amounts of sphalerite and galena. The ore minerals commonly replace carbonized plant matter, the cementing material of the sandstone host rock, and detrital grains of quartz and feldspar. The ore deposits are younger than the host rocks, but the source of the metals is unknown. Channels at the base of the Shinarump member, interbedded sandstone and mudstone, and the presence of abundant carbonaceous material have all been recognized as playing an important part in the localization of ore.

Field studies by the authors in the summer of 1956 indicate that the Shinarump member in the White Canyon district was deposited by two separate systems of streams, one carrying sediments having a source to the east of Elk Ridge—this corroborates a concept first suggested by Miller (8)—and the other carrying sediments having a source somewhere in Arizona far to the south of the White Canyon district. The sediments deposited by the streams of these two channel systems appear to coalesce in the Red Canyon area. These studies further indicate that the minable uranium deposits of the White Canyon district are all within the boundaries of the channel system that developed from the east (hereinafter termed the Elk Ridge-White Canyon channel system), and that the nature of the channels and the lithologic characteristics of the sediments deposited in this channel system make these rocks a much more favorable host for uranium deposits than the Shinarump deposited in the channel system that had a southern source.

The purpose of this report is to describe that part of the Shinarump member deposited in the Elk Ridge-White Canyon channel system and to discuss the effects of this channel system on the distribution of uranium deposits within the White Canyon district. The possibility of applying the channel system concept to exploration for uranium elsewhere on the Colorado Plateau is also discussed.

ELK RIDGE-WHITE CANYON CHANNEL SYSTEM

Lithology

The Shinarump member of the Chinle formation deposited in the Elk Ridge-White Canyon channel system is composed of light-gray to pale yel-

lowish-orange fine- to very coarse-grained conglomeratic sandstone complexly interbedded with gray to greenish-gray mudstone. Carbonaceous material in the form of carbonized leaves, stems, and partially calcified logs is sparse to abundant. An interbedded sandstone-mudstone unit is commonly present in deeper scours, and a massive conglomeratic sandstone unit commonly occurs in blanket-like layers at the top of the member. Pebbles are as much as 5 inches in size, and are subrounded. Most of them are composed of quartz, the rest being quartzite and chert.

Direction of Sediment Transport

Trends of individual channels (Richard Q. Lewis, Sr., and Tommy L. Finnell, written communications, 1956) and the average direction of dip of crossbedding (9) indicate a westerly to southwesterly direction of transportation of the sediments in the Elk Ridge and Deer Flat areas (Fig. 1). In the southern part of the thin fan-shaped alluvial deposit west of Deer Flat most channels trend westerly and southwesterly; in the central and northern part of the deposit they trend predominately to the northwest (14). Trends based on the direction of dip of crossbedding are thought to vary less in the lower part of the Shinarump member than in the upper part. After the lower channel scours were filled with sediments the streams that deposited the upper part probably did considerable meandering.

Further indication of the general westerly direction of transportation of the sediments of the Shinarump member deposited by streams of the Elk Ridge-White Canyon channel system is a decrease in the amount of pebbles and size of the largest pebbles westward from the Elk Ridge area.

Source of Sediments

The predominance of quartz pebbles and quartz and feldspar grains in the sandstone plus the general westerly direction of transport of sediments combine to indicate that the sediments deposited in the Elk Ridge-White Canyon channel system were derived from a granitic and metamorphic terrane to the east. The ancestral Uncompahgre highland, which was about 80 miles to the northeast and about 150 miles directly to the east of the Elk Ridge area, seems to have been the most logical source area.

Boundaries and General Characteristics

Figure 1 shows the authors' concept of the approximate boundaries of the Elk Ridge-White Canyon channel system. This concept is based on the results of work by Lewis (4, 5) and Lewis and Campbell (6, 7) in the Elk Ridge area; by Finnell (2) in the Deer Flat area; by Trites (11, 12) in the White Canyon and Red Canyon areas; and on field studies by the authors throughout the White Canyon district. Sediments deposited in the Elk Ridge-White Canyon channel system have not been traced east of the Elk Ridge area because most of them are buried beneath younger sediments in that direction.

In the Elk Ridge and Deer Flat areas the subparallel boundaries of the

Shinarump member suggest a sinuous alluvial valley 3 to 6 miles wide. Lewis and Campbell (7) have presented evidence of a structural trough which was subsiding in the Elk Ridge area during deposition of the lower part of the Chinle formation and which may have influenced the boundaries of deposition of the Shinarump member. North and south of the boundaries of the channel system in the Elk Ridge and Deer Flat areas, the Shinarump member has not been recognized, although a few small seemingly isolated sandstone lenses may correlate with it. West of the Deer Flat area, the boundaries of deposition of the Shinarump member and trends of the channels diverge and indicate that the Elk Ridge-White Canyon channel system debouched into an alluvial fan-shaped deposit, the apex of which is approximately at Deer Flat.

In general, the Shinarump member is thicker and individual channels are more closely spaced in the Deer Flat area than in the west-central part of the fan-shaped deposit. The diverging of distributary streams west of Deer Flat probably resulted in greater distances between the channels and caused the sediment load to be spread out in thinner deposits over wider areas.

Along the northern and northwestern boundaries of the fan-shaped deposit in the White Canyon area, the Shinarump member interfingers and grades into gray sandy mudstone and thin local beds of shaly coal. The shaly coal beds are as much as 4 feet thick and have a lateral extent of several hundred feet. Apparently the streams that deposited the Shinarump died out in muddy lakes and swamps in this area. Much of the mudstone may be the time equivalent of sandstone of the Shinarump member, but the mudstone is commonly mapped as part of the Monitor Butte member of the Chinle formation.

In the west-central part of the fan-shaped deposit in the White Canyon and Red Canyon areas the Shinarump member is characterized by thin scattered lenses of coarse sandstone with a few shallow channel scours at the base. Between these sandstone lenses are large areas in which the Shinarump is absent or is represented by gray sandy mudstone that is probably the time equivalent of the sandstone. The thinness and discontinuity of the sandstone lenses in this area are thought to be indicative of proximity to the outer margin of the fan-shaped deposit (Fig. 1).

The southwestern margin of the Elk Ridge-White Canyon channel system in the Red Canyon area is very poorly defined because much of the Shinarump member in this area is buried beneath younger rocks of the Red Rock Plateau. Therefore, the boundary shown on Figure 1 is largely hypothetical. Also, the rocks of the Elk Ridge-White Canyon channel system appear to coalesce in this area with sediments of the Shinarump member which were transported northward into the White Canyon district from a source to the south. The sediments of the Shinarump that were derived from the south differ from the Shinarump deposited in the Elk Ridge-White Canyon channel system in that they form a blanketlike layer consisting predominantly of light-gray fine- to coarse-grained sandstone that locally contains numerous gray mudstone pebbles and abundant interstitial gray mudstone. The layer is further characterized by very sparse amounts of carbonaceous material, scattered silicified

logs, muscovite, rib- and furrow-type ripple marking (10) as well as cross-bedding, and by coarse conglomeratic sandstone being found for the most part only in sparse amounts at the base of the unit. Channel trends, dips of cross-strata, and rib and furrow markings indicate that the sediments derived from the south were transported in directions ranging from east-northeast through north to west-southwest in the Red Canyon area. Along the Colorado River a few miles west-southwest of the postulated margin of the Elk Ridge-White Canyon channel system deposit, the Shinarump is as much as 60 feet thick and is apparently of the type that came from the south. Exposures of this blanketlike type Shinarump, as much as 100 feet thick, are common along the San Juan River at the extreme southern end of the White Canyon district.

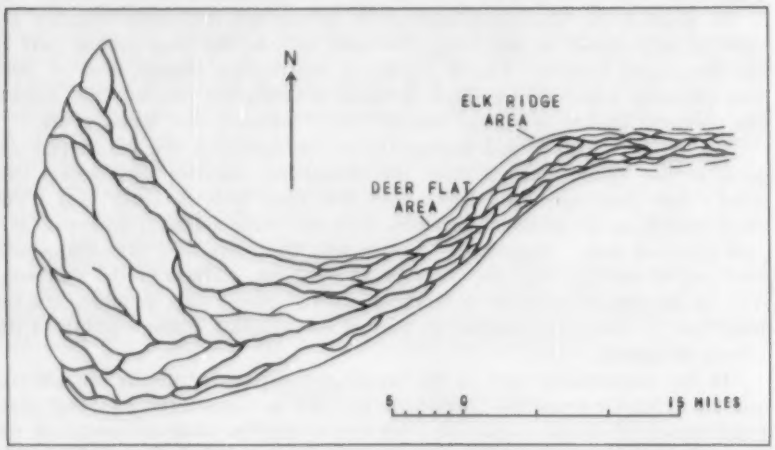

FIG. 2. Schematic diagram of idealized Elk Ridge-White Canyon channel system, White Canyon district, San Juan County, Utah.

Near the north end of Red House Cliffs (Fig. 1) thin discontinuous lenses of mottled purple, red, and white siltstone, sandstone, and conglomeratic sandstone have been mapped by Thomas E. Mullens (written communication, 1955) as the Shinarump member, largely because they occur at the base of the Chinle formation. These sandstone lenses are lithologically unlike the Shinarump in the White Canyon district which was derived from the south, and they do not correlate well with rocks deposited in the Elk Ridge-White Canyon channel system. These lenses probably were derived from a source somewhere to the east, but they are not well understood and are tentatively excluded from rocks deposited in the Elk Ridge-White Canyon channel system.

In general, the Elk Ridge-White Canyon channel system seems to have been formed by a large braided stream composed of a maze of bifurcating and intermingling waterways ranging in size from small creeks to master streams 1,000 feet or more in width. (Fig. 2 shows a schematic diagram of the

idealized channel system.) Gradient was probably only a few feet per mile, and the channels were choked with an overload of sediments. Alternate scouring and filling took place continuously as the water level fluctuated between flood and low-water stages. West of Deer Flat the stream emerged from its valley, the gradient became even less, and a fan-shaped deposit was formed. This "fan" was bounded on the north and northwest by muddy lakes and swamps and on the southwest by somewhat similar sediments advancing from the south.

Lithologic Units

The sediments of the Shinarump member deposited in the Elk Ridge-White Canyon channel system are divided into an interbedded sandstone-mudstone unit and a blanketlike massive sandstone unit.

Sandstone-Mudstone Unit.—This unit underlies the massive sandstone unit and commonly fills channel scours and other low areas. Sandstone and mudstone were deposited almost simultaneously in some places as interfingering lenses of sandstone and mudstone or as lenses of sandstone enclosed by mudstone. In other places alternating deposition of sand and mud formed interbedded sandstone and mudstone. Probably sand was being deposited by faster currents in the deeper parts of scours and in channel sandbars at the same time that relatively slow currents were depositing mud in slipoff slopes, flood plains, abandoned channels, and backwater areas. In general, sandstone makes up approximately 50 to 80 percent of the volume of sediments in the channel scours. The sandstone in this facies is light gray to light yellowish-gray, fine- to very coarse-grained, sparsely conglomeratic, and shows little cross-stratification. The mudstone is gray, massive, and contains some siltstone. Carbonaceous plant debris and partially calcified logs are abundant in both the sandstone and the mudstone.

Massive Sandstone Unit.—This unit overlies the sandstone-mudstone unit and in interchannel areas may be the only part of the Shinarump member present. The sandstone is crossbedded, light gray to light yellow gray, medium- to very coarse-grained, and conglomeratic. Carbonaceous plant debris and logs are sparse. Gray massive mudstone is abundant locally but is generally absent or present in only minor amounts.

In many places the massive sandstone unit fills scours cut in the underlying sandstone-mudstone unit. This suggests that the two different units may be due to two separate periods of deposition. On the other hand, it is conceivable that deposition of the two units was essentially simultaneous, and that the sandstone-mudstone unit was deposited in channels and low areas and the massive sandstone was deposited as a blanket once the channels were filled.

Channel Scour Characteristics

Channels of the Elk Ridge-White Canyon channel system incised in the Moenkopi formation range from a few feet to 1,000 feet in width. The depth of these channels generally ranges from about 15 to 25 feet, but some examined

by Trites, Finnell, and Thaden (14) are as deep as 50 feet or as shallow as 4 feet. The relatively shallow depths of channels in the Elk Ridge-White Canyon channel system contrast sharply with depths of 75 to 150 feet reported by Witkind (15) in Monument Valley, Utah and Arizona.

Figure 3 shows schematic cross sections of types of channels present at the base of the Shinarump member in the Elk Ridge area. Figure 3a represents an asymmetrical channel with mudstone on the slipoff slope, sandstone in the deeper part of the scour, and interfingering mudstone and sandstone between. From the shape of this scour and the relative positions of mudstone and sandstone it may be inferred that the stream was bending to the

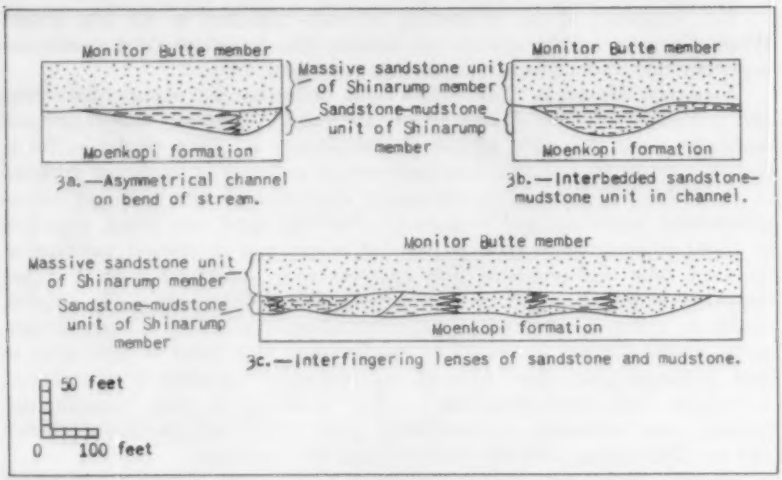

FIG. 3. Schematic cross sections of types of channels at the base of the Shinarump member of the Chinle formation in the Elk Ridge area, White Canyon district, San Juan County, Utah.

left at this point. Inferences of this sort should be helpful in the attempt to trace channels behind outcrops or in front of drilling and mining operations.

Figure 3b shows a channel filled with the interbedded sandstone-mudstone unit which is overlain by the massive sandstone unit. The massive sandstone unit fills scours cut into the sandstone-mudstone unit. Figure 3c shows interfingering lenses of sandstone and mudstone of the sandstone-mudstone unit overlain by the massive sandstone unit.

EFFECTS OF ELK RIDGE-WHITE CANYON CHANNEL SYSTEM ON DISTRIBUTION OF URANIUM DEPOSITS

Sandstone-Mudstone Unit

All uranium deposits of any consequence in the White Canyon district are in channel fills and are confined to the sandstone-mudstone unit of the

Shinarump member. Apparently the combination of the presence of a channel and the lithologic characteristics of the sandstone-mudstone unit provided conditions favorable to ore deposition. Probably the transmissivity of channel-fill sandstone allowed easy passage of laterally moving ore solutions; interfingering sandstone and mudstone lenses provided local traps to guide the ore solutions; and the presence of carbonaceous material caused a chemical environment conducive to ore precipitation.

Relation of Ore Deposits to the Margin of the Channel System

Trites and others (14) have stated that all known high-grade ore deposits in the White Canyon area are within 3,000 to 15,000 feet of the margin of deposition of the Shinarump member. (Fig. 1 shows the location of these ore deposits.) A possible control such as the damming up of laterally moving ore solutions by pinchout of the Shinarump is suggested. On the other hand, it seems more likely that certain features of the Elk Ridge-White Canyon channel system may have caused this apparent grouping of ore deposits. Upon divergence of the streams to form the fan-shaped deposit, major drainage apparently tended to follow courses near the northern and southern margins of deposition, thus leaving large areas in the central and west-central portions of the fan to be covered only by sandy mudstone or thin scattered lenses of sandstone, both of which are relatively unfavorable for the formation of uranium deposits.

Regional Relationships

All known uranium deposits of any consequence in the White Canyon district are confined to that part of the Shinarump member deposited in the Elk Ridge-White Canyon channel system. Apparently the channels and lithologic characteristics of the Shinarump deposited in this channel system make it a much more favorable host for uranium ore bodies than the blanketlike Shinarump deposited by streams flowing into the White Canyon district from the south. The unfavorableness of the sediments of the Shinarump derived from the south as a host for ore deposits is probably due largely to the relative uniformity of its gross lithology (ore solutions would tend to be dispersed through the blanketlike unit rather than guided or trapped in certain parts of it) and to the sparseness of interbedded mudstone and carbonaceous material in it. It may be argued that this part of the Shinarump is favorable for large uranium deposits in Monument Valley (Fig. 1) and therefore should also be favorable beneath the Red Rock Plateau where it is essentially the same lithologically. There seems to be no completely satisfactory explanation for this apparent lessening of favorableness northwestward; but prospecting of the extensive outcrops of the Shinarump member in the western part of the Monument Valley district and along the San Juan River (and there are some very large channels in these areas) strongly indicates that—with the lone exception of the rather small Whirlwind mine—the Shinarump contains no significant uranium deposits in these areas. Consequently, estimates of

potential ore reserves within the whole White Canyon district must take into consideration the likelihood that the boundaries of the Elk Ridge-White Canyon channel system essentially delineate ground relatively favorable for minable uranium deposits within the district.

APPLICATION OF THE CHANNEL SYSTEM CONCEPT TO THE SEARCH FOR URANIUM

Study of rocks of the Shinarump member of the Chinle formation deposited in the Elk Ridge-White Canyon channel system suggests that the Shinarump member on the Colorado Plateau was formed by many coalescing channel systems in a wide shallow basin of deposition. It further indicates that sediments deposited by streams of certain of these channel systems are more favorable as hosts for uranium deposits than the sediments deposited in other channel systems. Geologic studies leading to the recognition, delineation, and understanding of these ancient channel systems may, then, be of great help in making regional appraisals of ore potential and in the search for new mining districts. Information on pebble assemblages from outcrops in Arizona and southwest Utah suggests that several different channel systems were present along the southern margin of the Colorado Plateau during deposition of the Shinarump.

ACKNOWLEDGMENTS

Thanks are due many geologists of the U. S. Geological Survey and the U. S. Atomic Energy Commission with whom the concept of the Elk Ridge-White Canyon channel system has been discussed. In particular, recognition should be given Miller (8) for his contribution to the understanding of the Elk Ridge-White Canyon channel system.

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GRAND JUNCTION, COLO.,
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SOME GEOCHEMICAL CONSIDERATIONS ON LEAD-ISOTOPE DATING OF LEAD DEPOSITS[1]

R. W. BOYLE

ABSTRACT

The validity of age determinations based on the lead-isotope ratios of galena or other lead minerals in deposits is questioned. A few simple examples are given to show that fractionation of lead isotopes in geochemical processes is probable. The geochemical processes through which lead has passed must be considered in detail before an age can be assigned to a lead deposit.

INTRODUCTION

In the recent geological literature, numerous papers have appeared describing the dating of lead deposits by using the ratios of the isotopes of lead in minerals such as galena. To me most of these papers seem to completely ignore certain features of the geochemical cycle of lead in nature. Furthermore, most investigators appear convinced that fractionation of the lead isotopes does not take place in natural processes. Even those writers who have taken note of the geochemical cycle of lead seem similarly convinced. Thus Shaw (1) in a recent paper has stated: "It is probable that lateral secretion from sediments is a valid process for the formation of some sulphide deposits, including galena. Whatever the mechanism of such ore-formation it is improbable that the isotopic proportions of a heavy element such as lead would be materially changed during transfer." Although I am an advocate of secretion processes for the origin of lead deposits, I cannot entirely agree with the second part of the quotation. Presumably Shaw meant that there is no fractionation by diffusion or similar processes during transfer. However, there are many other considerations, and as I shall presently show there is considerable geochemical evidence to suggest that fractionation of lead isotopes does take place, particularly during secretion processes. It follows, therefore, that ages calculated from the lead isotopic composition of galena and other lead minerals may not be valid.

In the following discussion I have based my argument upon a secretion hypothesis for the origin of lead deposits, because in my experience this hypothesis seems logical and appears to explain adequately most deposits that I have investigated both in the field and laboratory. I am fully aware, however, that not all will agree with this hypothesis, but I should like to point out that many of the arguments to follow apply with equal force to hypotheses based on granitization ideas, magmatic processes,[2] and even to those im-

[1] Published with permission of Director, Geological Survey of Canada, Dept. of Mines and Technical Surveys, Ottawa, Ontario.

[2] For a discussion outlining the necessity to study the detailed geochemistry of lead isotopes in magmatic and other processes see, Tugarinov, A. I., The geochemical significance of differences in the isotopic composition of lead in lead ore deposits: Izvest, Akad. Nauk. U.S.S.R. Ser. Geol., 1955, No. 4, p. 31–49 (In Russian, English translation available from, Library, Geological Survey of Canada).

probable vague hypotheses whereby lead is derived from deep within the earth (mantle). In the final analysis, any lead deposit represents a marked concentration of the element from a large volume of rock that has generally had a very complex history.

BONDING OF LEAD

Research by the present writer and numerous other investigators has shown that lead in minerals, rocks, and other natural materials is bound in several different ways. A few of these follow:

1. In feldspars, particularly those containing a high content of potassium: This lead probably replaces potassium because of similar ionic radii, K^{+}(1.33Å), Pb^{2+}(1.20Å), and other energetic considerations. Some may replace Ca^{2+}(.99Å). Part of the lead can be removed with strong acids. Fusions liberate it readily.

2. In carbonates, epidote, hornblende, pyroxene, muscovite, biotite, and fluorite: Most of the lead probably replaces either calcium or potassium. In the case of biotite and other micas some lead is of radiogenic origin being derived from uranium and thorium in zircon and other radioactive inclusions. Acids remove all of the lead from the carbonates and small amounts from the silicates. Fusions are necessary to recover the total lead content from the silicates.

3. In apatite: This lead probably substitutes for calcium, but some may be radiogenic in origin, derived from the small amounts of uranium in the apatite. Attack by strong acids liberates most of the lead. The remainder can be recovered by fusions.

4. In various sulfides: This is a consequence of the chalcophile nature of lead. It has been noted that sedimentary sulfides as well as sulfides in igneous and metamorphic rocks tend to collect appreciable amounts of lead. Most of this lead is held tightly within the sulfides and can only be removed by attack with strong acids or by fusions. In sapropelic material that has not undergone extensive diagenetic changes, it is probable, however, that the lead concentrated in the finely divided sulfides would be more readily liberated.

5. In zircons, allanite, and other common radioactive accessory minerals in granites, sediments, and other rocks. Much of the lead in these minerals is of radiogenic origin being derived from the disintegration of uranium and thorium in the minerals. Some of the lead is ordinary lead that may be held in minute inclusions of apatite and other minerals in the accessories. The nature of the bonding of the radiogenic lead is difficult to ascertain, but it is probable that some resides in lattice vacancies in the parts of the crystals disrupted by radiation. Some of the lead in the accessory minerals can be removed by weak acids or solutions of ammonium acetate. By such methods Tilton (2) has shown that the acid-soluble lead in sphene, zircon, biotite-xenotime, monazite, microlite, columbite-tantalite, and uraninite differs markedly in its isotopic composition compared to the isotopic composition of the lead in the sample as a whole. Without going into details these data suggest that the lead isotopes have different bond strengths in the various minerals. Similar

work by Zhirov et al. (3) has shown that the isotopic ratios of lead differ in successive acetate leaches of allanite, and they have concluded that the lead isotopes have different bond stabilities.

6. Adsorbed to the surface of clay minerals, inorganic colloids, humic complexes, and iron, manganese, and aluminum hydroxides: The strength of the lead bond to these materials depends upon the degree of aging. Initially the bond is weak, and the lead is readily removed by weak acids, solutions of ammonium citrate and acetate, and in some cases by distilled water. This, in fact, is the basis of one of the methods of geochemical prospecting viz. testing of stream sediments. With aging some of the lead may enter the structures of these complex materials and will consequently become more difficult to remove. During sedimentation further aging occurs, and diagenesis followed by metamorphism will result in the lead being more strongly bound in the structures of micas, feldspars, etc.

7. Adsorbed to mineral surfaces along grain boundaries and other discontinuities in rocks: Some of this lead is radiogenic, derived, from uranium and thorium also adsorbed or in compounds at grain boundaries and other microstructures (4, 5). Most of this lead is loosely bonded and can be removed by weak acid, acetate, or citrate solutions.

MIGRATION AND CONCENTRATION OF LEAD

If one assumes a secretion process for the concentration of lead in deposits, two points must be considered.

1. The processes whereby lead is accumulated in the source rocks.
2. The concentration of lead from the source rocks.

Since it is not possible in this short paper to consider all rock types an example may be taken of a suite of sedimentary rocks derived from a Precambrian granitic area. I shall follow first a few of the possible courses that the lead isotopes may take during the weathering and sedimentation processes and then discuss the factors that may influence the fractionation of the lead isotopes during the concentration processes from the source rocks.

During the weathering and erosion of the parent materials, the readily leached lead isotopes at grain boundaries (generally highly radiogenic) may be delivered to one basin, lead from and in sulfides and silicates to a second, and resistant minerals such as zircon and monazite in which a large proportion of radiogenic lead is present to yet a third. Some lead will also remain behind in terrestrial sediments. Telescoping of the sedimentation processes is also possible, and basins containing all of the above types may be formed. The net result will be basins of sedimentary rocks each having lead of different isotopic compositions and incidently giving several different ages although all were derived from a single Precambrian source rock.

But this is not the full story. Chemical factors such as oxidation-reduction potential, sulfur potential, carbon-dioxide potential, pH, adsorption, and organic activity may also play a part in fractionating the lead isotopes during their migration in the weathering cycle and their precipitation in sedimentary basins. The hydrogeochemistry of uranium and thorium is also a factor to

be considered. Certain sedimentary basins may be enriched in these two elements, others impoverished in one or the other or both elements. This will lead to marked variations in the U/Th ratios from rock to rock and basin to basin, which in turn will have a marked effect on the accumulation of radiogenic lead with time. All these geochemical processes will give rise to sedimentary rocks whose initial lead isotopic compositions are completely different from those of their parent source rocks. The ratio of the lead isotopes in deposits deriving their lead from such rocks is, therefore, neither a measure of the age of the deposits nor the age of the sedimentary host rocks but is rather a function of the complex geochemical processes through which the lead may have passed.

Turning now to the details of the concentration of lead from rocks, it is easy to see how the isotopic composition of lead in deposits may be dependent upon the different bond energies of lead in rocks. It has been shown above that lead varies widely in its bonding in rocks, partaking of mineral structures in some cases and being loosely bonded in others. Since the bond strengths of specific isotopes may also vary as shown by the results of Tilton (2) and Zhirov et al. (3) this would permit differential mobilization of the isotopes followed by a selective concentration of specific isotopes under favorable circumstances. A series of experiments carried out by Starik et al. (6), by heating rocks and sublimating lead, have shown that the lead isotopes are in fact mobilized differentially. On heating samples of Karelian and Caledonian granites to 800° C, initial lead fractions enriched in radiogenic isotopes were obtained, and the isotopic constitution of successive sublimates of lead was apparently temperature dependent. These experiments simulate regional metamorphic and granitization conditions, and the results strongly suggest that lead possessing different bond energies will be mobilized differentially during relatively high temperature geological processes.

The excellent work of Tilton et al. (7) has shown that the various minerals in rocks vary widely in their lead isotopic composition. Since each mineral has a unique thermochemical stability it follows that the breakdown of one mineral will yield lead of one isotopic composition whereas another in the same rock will yield a different composition. During metamorphism and granitization it is well known that certain minerals break down to form new minerals whereas others are relatively stable. Such differential processes in rocks would, therefore, release lead having a specific isotopic composition while retaining lead of an entirely different isotopic composition. One can conclude from this that under certain conditions a selective mobilization and concentration of specific lead isotopes to form deposits is probable in geochemical processes where metamorphism and granitization are the responsible agents.

To generalize, it is probable that in certain cases, as during regional metamorphism or granitization, the conditions may be such that equal proportions of loosely as well as tightly bonded lead are set in motion and may be concentrated in deposits. The isotopic composition of the final product may, therefore, be homogenized and may approximate the integrated isotopic composition of the rock series from which the lead came. In other cases either the tightly bonded or the loosely bonded lead may be set in motion and be-

come concentrated. In some deposits the latter type of lead may reflect mainly the isotopic composition of the lead that is readily available from radiogenic sources, and hence the so called "anomalous isotopic ratios" are recorded. The detailed work of Robinson (8, p. 84) has shown that this actually takes place. While the situations outlined above are perhaps the extreme cases it must be borne in mind that all gradations in the intensity of the concentrating processes (i.e., severe, moderate, or mild) are probable, and it would be expected that the lead isotopic ratios in deposits would vary accordingly. It bears repeating that as a consequence of the degree of intensity of the concentrating processes the proportions of the various lead isotopes contributed by different minerals and different rock series may vary widely, and it is plainly obvious that without a detailed geochemical study of these factors one cannot assign an age to a lead deposit.

The extent to which the isotopes of lead are concentrated will be dependent on the free energy conditions that prevail between the site of the concentration of the lead isotopes and their source. If the energy level is high and marked free energy differences prevail between the source of the lead and its site of deposition, homogenization may take place, and any local irregularities will be swamped or smoothed out. The uniformity of the lead isotope ratio in deposits over extensive districts or geological provinces, as mentioned in the literature, may, therefore, reflect the geochemical processes and not the age of widespread mineralization. If only small differences in the free energy exist (as in limited and local secretion processes) the concentration of specific isotopes may take place.

A few examples will serve to illustrate the relationship of some of the above points to age determinations. Suppose one assumes a Precambrian sediment whose inherited lead [3] has an isotopic composition corresponding to Precambrian time. If this sediment contains no uranium or thorium and it is assumed that there is no fractionation of lead isotopes, any deposit derived from it will have a Precambrian isotopic ratio regardless of whether the deposit is secreted during Precambrian time or any period thereafter. It is not possible, therefore, to date the deposit unless the geological setting can be worked out. On the other hand, if the Precambrian sediment contains an abnormal amount of uranium and thorium, the radiogenic lead derived from these elements may in time ultimately exceed the amount of inherited lead. If a deposit is secreted from the sediment when this takes place the isotopic ratios will be anomalous, and no age can be assigned to the deposit. Exactly the same situation results if the accumulated radiogenic isotopes are secreted in preference to the inherited isotopes from a sediment containing a normal amount of uranium and thorium. If, on the other hand, large amounts of inherited lead are concentrated, the age of the deposit is again indeterminate because it would be impossible to differentiate the small amounts of radiogenic lead by an analysis. In other words, the small contribution of radiogenic lead would be swamped and completely obscured by the in-

[3] In this example the term "inherited lead" is used to designate the lead present in the rock at the time of its formation. "Radiogenic lead" is used to designate the lead derived by radioactive disintegration after the formation of the rock.

herited lead. From these examples it is readily apparent that the amount of accumulated radiogenic lead contributed to a deposit is the deciding factor in age determinations and must be known before any age can be assigned to a deposit. This requires a detailed study of the abundance of uranium and thorium in the source rocks and a knowledge of the differential mobility of the inherited and radiogenic lead isotopes during the geochemical processes that have led to the concentration of lead from the source rocks.

The above discussion by no means exhausts the factors that bear upon the migration and concentration of lead isotopes in nature. Nevertheless, a sufficient number of examples have been given to show that fractionation of lead isotopes may occur, and consequently geochemical processes must be considered *in detail* before any age can be assigned to a lead deposit.

CONCLUSIONS

To conclude, I am of the opinion that fractionation of the lead isotopes takes place in geochemical processes, particularly in secretion processes. I would further stress that the lead isotope ratios recorded from deposits are the result of various geochemical processes through which the lead has passed, and that they are not, except in certain special cases, a function of the age of the deposit.

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June 2, 1958

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SCIENTIFIC COMMUNICATIONS

OCCURRENCE OF JORDANITE AT BALMAT, NEW YORK

JOHN S. BROWN

During the late 1930's, occasional pieces of a strange lead mineral that looked like dull-colored and, in some cases, rather platy galena were found on the long conveyor belt between primary and secondary crushers. Some analytical work was tried, inconclusively, and a watch was kept for points of origin in the mine. In 1939 a fair-sized nest of the odd mineral showed up in the back of the 1300 D-1 drift and samples were obtained for analysis and sectioning.

Complete analyses on carefully selected pure material, by L. E. O'Neil, St. Joseph Lead Company chemist, yielded the following results:

Pb	*Zn*	*Fe*	*Mn*	*As*	*Sb*	*S*	*Total*
69.87	0.10	1.21	0.43	9.85	1.38	17.55	100.39

At that time the mineral was judged to be nearest to jordanite in composition and it has generally been referred to as jordanite ever since by Balmat mill men and geologists.

The original occurrence was in the form of a bunch a few inches across and some minor wispy disseminations in a diopsidic silicated marble. Thin sections showed generally 50 to 75 percent diopside, 10 to 25 percent carbonate, (dolomite), a little chlorite, and jordanite.

The jordanite clearly replaced carbonate, in some cases with roundish forms convex against carbonate. A little chlorite marginal to the jordanite, probably of later date, commonly was present. Polished sections of the more massive mineral in some cases showed a remarkable very finely banded twinning, the bands strongly anisotropic but differently oriented. An eutectic type of graphic intergrowth was present in all of several sections, often hard to see and only at high magnification, or in oil immersion. It seemed to cut across the twinning where present. Widespread, fairly even pitting in two directions commonly was present, quite different from the customary triangular pits of galena. The polished surfaces were almost galena white, but slightly harder than galena. The larger masses of the mineral show fairly good cleavage of a platy character, in two directions.

Galena was present around the borders of the jordanite in some places, and a polished section of the two in contact indicated fairly clearly that galena was later and veined the jordanite.

Associated with the jordanite occurrence as a minor accessory are small

amounts of a dark copper mineral, perhaps tennantite, a selected sample of which analysed as follows:

Cu	*Pb*	*Zn*	*Fe*	*Mn*	*As*	*Sb*	*S*	*Total*
33.68	None	3.70	4.27	0.74	20.70	0.17	27.86	92.12

A polished section from this sample showed considerable included nonmetallic gangue, perhaps diopside, not carbonate. The ore mineral appeared to be isotropic. Relations to jordanite were not observed.

Various small amounts of material resembling the jordanite have been found in later years and other localities in the mine but have not been positively identified as the same. Indeed, analysis in one or two cases seemed to prove they were not, as the specimens lacked the necessary arsenic.

In analysis, the mineral appears to be very close to either jordanite, or gratonite,[1] but on the basis of the definite cleavage and strong anisotropism seems to fit better with jordanite.

The original showing is still in existence but over a main haulageway and so dusted over that little or nothing can be seen of it. There is no possibility, at present, of supplying jordanite to collectors in any appreciable quantity.

ST. JOSEPH LEAD CO.,
BONNE TERRE, MO.,
Nov. 3, 1958

LEAD ISOTOPES FROM BALMAT AREA, NEW YORK

JOHN S. BROWN AND J. LAURENCE KULP

Incidental to an extended study of lead isotopes in Mississippi Valley type ores, particularly in the southeast Missouri properties of the St. Joseph Lead Company,[2] a few determinations were made on samples from outlying areas. The samples reported here contrast the Precambrian mineralization at Edwards and Balmat with what may be Mississippi Valley type deposits in the Paleozoic strata nearby.

The geology of the Balmat area has been described in considerable detail in numerous publications, one of the latest being that of Brown and Engel (4) which contains citations to most of the available literature. The principal ore deposits consist of fairly massive replacements in Precambrian metamorphic dolomitic marble commonly assigned to the Grenville series. The chief ore minerals are pyrite and sphalerite, with small amounts of galena and, rarely, other lead-bearing minerals. These ores have been assumed to be of Precambrian age but geologic data for this conclusion are not compelling. In nearby areas, however, there are minor occurrences of galena and sphalerite in calcite-filled fissure veins of definite post-Cambrian age that cut Paleozoic strata.

[1] See Am. Mineralogist, vol. 25, no. 4, p. 255–270, 1940.
[2] In preparation for publication by Geol. Soc. Amer.

The isotopic composition of the lead was determined by standard mass spectrometric methods described elsewhere (2). The results and sample descriptions are given in Table 1. The Balmat and Edwards Mines are dominantly zinc-pyrite mineralization. The galena concentrate at Balmat is a byproduct. The jordanite (identified by chemical composition and physical properties) is a rare lead mineral. The galena at Edwards is non-commercial. The Rossie fissure vein occurs about 15 miles northwest of Balmat in Precambrian wall rock but similar veins nearby cut Paleozoic Potsdam sandstone and suggest a Mississippi Valley type deposit.

TABLE 1

ISOTOPIC COMPOSITION OF LEAD MINERALS FROM BALMAT AREA, NEW YORK

Sample description	204	±	206	±	207	±	208	±
Fine grained galena	1.000		16.96		15.54		36.77	
concentrate 60% Pb	1.423	.007	24.14	.02	22.12	.01	52.32	.03
Balmat Mine, New York								
Jordanite*	1.000		17.06		15.62		36.99	
Balmat Mine, New York	1.415	.013	24.14	.02	22.10	.05	52.34	.04
1300 Level								
Coarse galena in limestone	1.000		16.80		15.60		36.92	
Edwards Zinc Mine	1.422	.005	23.89	.01	22.19	.02	52.50	.02
2100 Level								
Calcite vein, with galena	1.000		19.28		15.63		39.61	
Rossie, New York	1.324	.004	25.53	.03	20.70	.01	52.45	.03

* Pb 69.9%, As 9.9%, Sb 1.4%, S 17.6%, Fe 1.2%.

The isotopic composition of the Balmat-Edwards samples is closely similar and indicates a Precambrian age. According to the latest estimate of lead isotope evolution in the crust (3) using the basic Houtermanns-Holmes model, the age of deposition is 1050 ± 100 m.y. ago. The Rossie deposit shows lead with an anomalously high Pb^{206}/Pb^{204} ratio indicating post-Cambrian lead derived from a granitic source possibly by the inhomogeneous extraction mechanism that appears to account best for the isotopic data in the Mississippi Valley type deposits (3).

This case illustrates the practical application of lead isotope data in determining both age and source of a base metal deposit.

The fact that the Precambrian ores have about the same age (1 b.y.) as the Grenville metamorphism, as determined by uranium-lead (5), potassium-argon, and rubidium-strontium (1) determinations, shows again (5) that metallic mineralization in the Shield commonly follows closely after the regional metamorphism.

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St. Joseph Lead Co.,
Bonne Terre, Mo.,
AND
Lamont Geological Observatory,
Columbia University,
Nov. 3, 1958

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DISCUSSIONS

TEMPERATURES AND DEPTHS OF FORMATION OF SULPHIDE ORE DEPOSITS AT GILMAN, COLORADO

Sir: T. G. Lovering's paper in Economic Geology, Vol. 53, p. 689–707, presents a most interesting application of thermoluminescence glow-curves, which suggest that the partial or complete suppression of glow-curve peaks can be inferred to provide an indication of the temperature to which carbonate rocks have been heated. As stated in the paper (p. 701), this application is based on observations by Daniels and Saunders of the University of Wisconsin, on the suppression of glow-curves from limestone in the vicinity of igneous contacts. Unfortunately, there is reason to doubt the usefulness of the results due to the presence of metasomatic changes in the rocks at Gilman.

Lovering correlates the suppression of glow-curve peaks with liquid inclusion filling temperatures for five specimens of four rock types showing different degrees of metasomatism and from widely separated localities. In general, his results from the two techniques appear to indicate a broad correspondence in temperatures to which the rocks may be assumed to have been heated, but he states quite clearly that this may be fortuitous and that much more work should be done to properly evaluate thermoluminescence glow-curves from carbonate rocks as a useful geothermometry tool.

In order to validate the use of glow-curves for geothermometry in the Gilman area it is assumed that the glow-curves from the dolomites and the limestone are more or less comparable (p. 702). An expansion of this assumption would be that glow-curves can be obtained from most carbonate rocks, and, for relatively unaltered sedimentary limestones at least, this appears to be the case (Daniels and Saunders et al., various mimeographed reports). However, for any investigation of thermoluminescence a very important further assumption must be concerned with metasomatic addition or subtraction of material. In the vicinity of the Gilman ore deposits the original limestones have suffered three stages of metasomatic dolomitization (p. 693 and 700) and in and near the ore bodies there have undoubtedly been additional changes in the wall rocks during the introduction of the ore minerals and gangue, through the addition or subtraction of "suppressing" or "activating" elements in the mineral phosphors. From the same point of view, the introduction or movement of radioactive elements during the metasomatism may have "recharged" the phosphors, assuming that they had been previously "discharged" by elevated temperatures.

That the above considerations are most vital can be seen from consideration of some of the essential requirements for the presence or absence of thermoluminesence in minerals (and hence in rocks):

a) The presence of certain elements in trace or larger amounts act either to initiate or increase the amount of thermoluminescence. These are the so-called "activators" and are generally some of the metallic elements.

b) The presence of other elements in trace to large amounts may partially or completely suppress thermoluminescence, even though suitable activators may be present. These are the "depressants" (also variously termed poisons or killers), with iron being the best known.

c) The presence of even weak radioactivity in rocks appears to be sufficient to build up the extra electron content of the crystal lattices of suitable mineral phosphors, so that when the rock is heated the phosphors will emit the extra energy in a thermoluminescence glow-curve having one or more peaks. Once this excess energy has been discharged the glow-curve cannot be readily reproduced unless it is recharged by exposure to a high intensity source of nuclear radiation as done by Daniels and Saunders et al.

It should be obvious from the above very elementary summary that simple *thermal* metamorphism of carbonate rocks undoubtedly does partially or completely suppress the peaks of the rock's glow-curve and thus should provide an approximate idea of the temperature rise. However, it is equally true, that if the content of activators or suppressants has been changed by metasomatism, the change in the glow-curve may bear *absolutely no relationship* to the rise in the temperature of the rock. Furthermore, assuming complete thermal suppression of the glow-curve followed by hydrothermally introduced radioactive elements, the glow-curves might be partially or completely reformed.

The foregoing comments have been principally concerned with carbonate rocks, but they apply equally to hydrothermally introduced ore bodies in other rock types, notably chloritized extrusives and, with lesser certainty, altered tonalite. In some cases, instead of the hydrothermal alteration suppressing the thermoluminescence it actually appears to have created a zone of thermoluminescence immediately adjacent to the ore, although the phenomenon is lacking in the country rock at distances varying from a few feet to 40 feet from the contact (McDougall, Econ. Geology, vol. 49, p. 717–726).

It is unfortunate that comparatively little published information is readily available on the work of Daniels and Saunders and their various associates, since (in the writer's opinion) the phenomenon appears to provide numerous possibilities for economically useful applications in the field of geochemistry in particular and quite possibly (as applied at the University of Wisconsin and by Lovering) in the fields of geothermometry, age determination and correlation.

It is sincerely hoped that the foregoing comments will be taken as constructive criticism and may even encourage further research into the various possibilities.

David J. McDougall

Department of Geology,
Loyola College,
Montreal, Quebec,
Nov. 1, 1958

TUNGSTEN MINERALIZATION IN HONG KONG AND THE NEW TERRITORIES

Sir: Professor Davis' note in this Journal (June–July, 1958) on the above subject appears to contain no evidence showing that "mineralization took place at much lower temperatures than have so far been postulated" (p. 481). Some of the field evidence cited is incorrect.

The section from west to east across Devil's Peak (Fig. 6, p. 486) if compared with the published map and description elsewhere (3) shows serious discrepancies. Though generalized the length of section is 4,000 feet and height 2,000 feet (1,600 feet if the left hand vertical portion is deducted), but Devil's Peak is only 720 feet above sea level. Even if the vertical scale is exaggerated the section bears no relation to the contours on the topographical map (Sheet 19, 1:20,000 Hong Kong). The huge mass of greisen (ca. 2000 by 500 feet in section) is entirely imaginary as is the underlying pegmatite. This cannot be a section along the vein as it does not cut the "porphyry" and veins in this area strike at 320–340° (true bearings) not east–west. No large masses of greisen, pegmatite or wolfram ore (1,500 feet long by 50 feet thick) can be seen on Devil's Peak itself. A small outcrop of greisen occurs a little to the north but would not be intersected by a west to east section across the summit. Partly recrystallized rhyolitic ignimbrite is continuously exposed on Devil's Peak and overlies a normal granite. The only large mass of greisen known in Hong Kong was found by the writer on Hai Wan to the north of Devil's Peak and here it is not capped by the ignimbrite (or "porphyry"). However, this is greisenized ignimbrite not greisenized granite; the latter being to date unknown in Hong Kong. Finally, apart from the old adit south of Devil's Peak (2, Fig. 4) macroscopic beryl and wolfram are not very common in this area. Thus no significant wolfram ore occurs on Devil's Peak itself. Disseminated wolfram and beryl do occur in the greisen but no detailed quantitative data is available. Even if Professor Davis * is calling another hill Devil's Peak his section does not fit any other locality in Hong Kong.

Similar remarks could be made about Castle Peak (Fig. 5, p. 486) where granite is thrust over the older sedimentary rocks and flaser gneiss and schist occur on the contacts. No wolfram ore body has been found with one-tenth the dimensions shown (ca. 1,500 × 200 ft) neither are the sedimentary rocks horizontal, they are folded along NE–SW axes.

Contact effects are common adjacent to wolfram-bearing pegmatite and quartz veins (cf. Davis, p. 486) and have been briefly described by Ruxton (3, p. 456–457). Since most of the country rock surrounding the granite is rhyolitic ignimbrite that has been converted into a seriate-porphyry by contact metamorphism, little extra effects are expected from pegmatites and quartz veins.

* Confusion of location was also shown in the illustration purporting to be "Basalt and other islands in Rocky Harbour, Mirs Bay" (Davis (1), facing p. 35). Not only is Rocky Harbour not in Mirs Bay, but these islands are the Ninepin Group on the left and Steep Island on the right; moreover they are not in Rocky Harbour.

It is strange that Davis should refer to his book on "The Geology of Hong Kong" (1) in a paper published in ECONOMIC GEOLOGY. Not only is this book a poor copy of Williams' report (4) but in it there is a denial of the splendid work in economic geology carried out by the Canadian geologists in Hong Kong though most of this work can be found repeated without acknowledgment. Thus page (ii) of the preface states: "The report, invaluable though it was, has several major omissions including no mention of the economic geology." Economic geology was discussed in four places in Williams' report; one section (page 182–233 inclusive) was headed "Non-Metallic Mineral Deposits, Building Materials by R. W. Brock." Chapter 9 of Davis' book (1, p. 124–154) is a faithful reproduction with minor editing of R. W. Brock's original section.

B. P. RUXTON

SHREWTON, ENGLAND,
Nov. 10, 1958

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REVIEWS

THIRTEEN REVIEWS OF RECENT RUSSIAN LITERATURE ON ECONOMIC GEOLOGY

The following books not hitherto noticed in ECONOMIC GEOLOGY, among others, have been received by the reviewer since mid-1957. Works of which publication has not yet been completed are denoted by an asterisk. Of the few periodical publications listed, most are new journals concerned with economic geology.

Opyt razrabotki teoreticheskikh osnov geokhimicheskikh metodov poiskov rud tsvetnykh i redykh metallov. (Principles of geochemical prospecting: techniques of prospecting for non-ferrous ores and rare metals.) BY I. I. GINZBURG. Pp. 299, figs. 72. Gosgeoltekhizdat, Moscow, 1957. 11r. 70k.

An English translation of this fundamental text on the principles and practice of geochemical prospecting for ore deposits is being prepared by Dr. V. P. Sokoloff of U. S. Geological Survey, for publication by Pergamon Press.

Osnovy energeticheskogo analiza geokhimicheskikh protsessov. (Fundamentals of energy analysis related to geochemical processes.) BY V. I. LEBEDEV. Pp. 342, figs. 71. University Press, Leningrad, 1957. 23r. 60k.

This text-book of geochemistry is along the lines of the theory of energetics of Fersman, but unlike the writings of that great traveller there is little to suggest that the author has ever vacated his laboratory stool to look at geological processes in the field. The work is in two sections: (1) the physical and chemical foundations of geochemistry, and (2) the application of fundamental geochemistry to the understanding of isomorphism, of migration of elements within the earth's crust, and such-like topics.

Trudy Geologicheskogo Muzeya imeni A. P. Karpinskogo. (Transactions of the Karpinsky Geological Museum.) Vol. 1. Pp. 165, pl. 14. Academy of Sciences, Moscow-Leningrad, 1957. 12r. 60k.

This first volume of yet another new periodical publication from Russia sets a high standard and is well produced. It comprises articles on the stratigraphical sub-division of the Jurassic system in Europe, on a petrographical study of a highly differentiated basalt lava, and on aspects of regional palaeontology and stratigraphy.

Poiski mestorozhdenii urana. (Prospecting for uranium deposits.) BY V. G. MELKHOV AND L. CH. PUKHAL'SKII. Pp. 212, figs. 63. Gosgeoltekhizdat, Moscow, 1957. 12r. 55k.

A handbook for prospectors, comprising a good account of the mineralogy of uranium (pp. 9–84), a review of the principal types of deposits and of theories on their genesis (pp. 85–103), and a comprehensive description of (principally radiometric) prospecting methods (pp. 104–211). No localities are mentioned, nor are references lited.

Spravochnik po radiometrii dlya geofizikov i geologov. (Reference book on radiometry for geophysicists and geologists.) Edited by V. I. BARANOV. Pp. 163, tables 95. Gosgeoltekhizdat, Moscow, 1957. 8r. 40k.

A compilation of tabular matter relating to the natural radioactive elements, with a review of radiometric exploration techniques and a description of the various kinds of radiometric equipment used to search for uranium in Russia.

Voprosy geologii urana. (Contributions to the geology of uranium.) Pp. 160, pl. 28. Atomizdat, Moscow, 1957. 9r. (Paper covers.)

A compilation of a dozen papers comprises some unimportant contributions concerned with uranium in sedimentary rocks including coals, and more useful mineralogical works on nenadvekite (which is distinguished from coffinite), on a new uranium silicate named ursilite, and on the differential thermal analysis of many of the commoner secondary minerals of uranium.

Geologiya mestorozhdenii redkykh elementov. Vyp. 1. Redkometal'nye karbonatity. (Geology of deposits of the rare elements. Part 1. Rare-metal carbonatites.) Edited by A. I. GINZBURG. Pp. 128. Gosgeoltekhizdat, Moscow, 1958. 5r. 75k. (Paper covers.)

The volumes scheduled to appear in this series are concerned with (1) rare-metal carbonatites; (2) columbite granites; (3) rare-metal pegmatites; (4) lithium deposits outside the U.S.S.R.; and (5) papers on the geochemistry of the rare earths. The first of these, an assiduous compilation of the economic geochemistry of carbonatites, is almost wholly based upon western literature and there is no more than passing mention of the carbonatites in the U.S.S.R., where pyrochlore-bearing carbonatite complexes occur in the Kola peninsula (three masses), the northwest of the Siberian platform, eastern Sayan in the Irkutsk oblast, and the Aldan mountains of Yakutia (two masses). A literature list of 132 items includes only 16 Russian papers.

Zakonomernosti obrazovaniya i razmeschcheniya mestorozhdenii titanovykh rud. (The regularities of formation and disposition of titanium ore deposits.) BY I. I. MALYSHEV. Pp. 272. Gosgeoltekhizdat, Moscow, 1957. 11r. 10k.

This compilation on the economic geology of titanium ore deposits throughout the world is in three parts, the first dealing with the geochemistry and mineralogy of titanium, the second with theories on the behavior of titanium in magmatic differentiation, and the third reviewing world resources. Russian deposits are described briefly from Kola and Karelia (associated with alkalic rocks), from the Ukrainian shield (ilmenite in gabbro-anorthosite, with derived placers of Mesozoic and Recent age), from the titanium province of the Urals (many kinds of deposit), and from various regions in the east (mainly in anorthosite, but not yet much studied).

Daiki i orydenenie. (Dykes and ore formation.) BY KH. M. ABDULLAEV. Pp 232, figs. 98. Gosgeoltekhizdat, Moscow, 1957. 16r. 55k.

Some years ago Abdullaev published a volume of evidence correlating mineralization with granitoid intrusions. Now he has produced this lengthy work illustrating the extent to which mineralization may be structurally and geochemically controlled by dykes. The work is the more interesting in that the examples quoted are almost all drawn from Russian literature.

Geologiya Narymskogo massiva granitoidov na Yuzhnom Altea. (Geology of the Narymskii granitoid massif in the Southern Altai.) By G. H. Shcherba. Pp. 216. Kazakhstan Academy of Sciences, Alma-Ata, 1957. 16r. 80k.

A memoir on the structural geology, petrology, mineralogy and petrogenesis of a Variscan granite massif concludes with very brief notes on tin mineralization.

Pozdnemezozoiskie intruzii tsentral'nogo Sikhote-Alinya i svyaz's nimi orudeneniya. (The late Mesozoic intrusions of central Sikhote-Alin and their associated mineralization.) By E. P. Izokh and others. Pp. 247. Gosgeoltekhizdat, Moscow, 1957. 16r. 60k.

The granites of Sikhote-Alin are heavily mineralized and presumably form one of the sources of the rapidly expanding production of tin in Russia. This well-produced memoir gives a full description of the petrography and geochemistry of the central intrusions (40,000 km²) which in their mineralogical make-up bear a close similarity to the stanniferous granites of S.E. Asia.

***Zhelezorudnykh mestorozhdenii U.S.S.R.** (Iron ore deposits of the U.S.S.R.) 20 volumes. Academy of Sciences, Moscow, 1958–1962.

It is announced by the Academy of Sciences that a series of twenty large volumes on the iron ore fields of the U.S.S.R. will be published in the next five years, each work reviewing the geology, mineralogy and genesis of an important group of deposits, with assessments of their potentiality for production and of the beneficiation work conducted on the leaner ores. The fields described are the magnetic ores and the oolitic ores of Kustanaisk in Kazakhstan (2 vols.), the ores of Altai-Sayansk (3 vols.), and of Central Kazakhstan, the high-grade and the quartzite ores of the Kursk magnetic anomaly (2 vols.), the Pri-Azov basin, the titanomagnetites of the Urals, the Angara-Pitsk and Angara-Ilimsk fields of Irkutsk (2 vols.), the chrome-nickel iron ores of eastern U.S.S.R., the iron ores of northwestern U.S.S.R., the Kirovsk basin (3 vols.), the Magnitogorsk deposits, and the deposits of Trans-Caucasia.

***Izbrannye trudy.** (Selected works) of A. I. Zavaritskii. In four volumes. Academy of Sciences, Moscow, 1956–1960.

The first volume in this standard edition of Zavaritskii's works, principally petrographical papers, appeared in 1956. Volume II, about to be published, reprints well-known petrographical memoirs on the alkaline rocks of the Urals and Western Siberia, including works on rapakiwi granites, on nepheline-syenites, and on the Ilmen mineralogical reserve. Volume III (1959) consists of the monograph on the iron ores of Gora Magnitaya, and volume IV (1960) comprises a monograph on the copper ores of the Urals and other works on economic geology.

C. F. Davidson

University of St. Andrews,
Scotland,
Aug. 6, 1958.

Bibliography and Index of Literature on Uranium and Thorium and Radioactive Occurrences in the United States. Parts 1–5. By Margaret Cooper. Pp. 472. Geol. Soc. of America, 1958. Price, $6.75.

The Geological Society of America has published as its Special Paper No. 67, "Bibliography and Index of Literature on Uranium and Thorium and Radioactive

Occurrences in the United States. Part 5: Connecticut, Delaware, Illinois, Indiana, Maine, Maryland, Massachusetts, Michigan, New Hampshire, New Jersey, New York, Ohio, Pennsylvania, Rhode Island, Vermont, and Wisconsin," prepared by Margaret Cooper of the U. S. Geological Survey on behalf of the Division of Raw Materials of the U. S. Atomic Energy Commission.

This book contains a section on bibliography (26 pages), a gazetteer for the States (38 pages), a geographical index (243 pages), and a subject index (165 pages). Factually it is a key to the literature on deposits in which uranium, thorium, and radioactive minerals are found in the northeastern United States. For many of the States there is also much detailed information in the indexes on the geology and the general mineralogy of the pegmatites, coal beds, sandstones, shales, beach sands, and other formations in which the uranium and thorium have been reported. Parts 1 to 4 of this bibliography were prepared by Margaret Cooper in the Division of Raw Materials of the U. S. Atomic Energy Commission and published in the Bulletin of the Society. These sections, which also include a bibliography, gazetteer, geographical index, and subject index, with detailed geological information for each area covered, are available as reprints for public sale by the Geological Society of America.

Introduction to Historical Geology, 2nd Edit. By R. C. Moore. Pp. 656; figs. 592. McGraw-Hill Book Co., New York, 1958. Price, $7.95.

This well known book has been completely revised and appears with a larger page more suitable for illustrations. As one leafs it over he is struck by the number of illustrations—almost as many as there are pages. About three quarters of these illustrations are new. They consist of cuts of fossils, fossil restorations, maps, charts, land forms, geologic columns, sections, air photos, and stratigraphic and structural features. The front pages show the geologic distribution of life forms and the back pages, a colored geologic map of Europe.

There are 21 chapters and 3 appendices. The first chapter deals with the materials and methods of historical geology. The second treats of evolution of life. The third chapter takes up the beginning of the earth and the fourth, the Cryptozoic era. The remaining chapters deal with the individual geologic periods concluding with the geologic record of man. Appendix A gives the characters of organisms represented among fossils; Appendix B, lithologic symbols for geologic sections; and Appendix C is an extensive glossary. Each chapter concludes with suggested readings and a long list of questions.

The text material dwells upon the principles of interpretation of observations of present geologic processes and is very clearly and interestingly written. The treatment of the Precambrian is very considerably expanded. The book also contains the first presentation of subsurface occurrences of geologic systems in North America and also there is included brief accounts of the economic resources of each geologic system. We also note that the terms Tertiary and Quaternary are replaced by Paleogene and Neogene. The reader can see in the text and illustrations the results of the author's extended knowledge and experience in petroleum geology.

It is a fine book and may well become the leading text book in historical geology.

Mineralogy and Geology of Radioactive Raw Materials. By E. Wm. Heinrich. Pp. 654. McGraw-Hill Book Co., New York, 1958. Price, $14.50.

The author, Professor of Mineralogy at the University of Michigan, has amassed a wealth of information in this weighty pioneer work. He gives a com-

prehensive survey of the great number of uranium minerals, how they occur, and how they were formed. He gives a genetic classification of radioactive deposits, which as all geologists know, any genetic classification has been very controversial. He is brave enough to state that Blind River, Ontario, is hydrothermal and classifies the Witwatersrand under mesothermal deposits. He does, however, list the chief arguments for both the modified placer and hydrothermal theories.

The book is made up of two parts—Part I of 152 pages is headed Mineralogy, and Part II, entitled Geology, consists of 404 pages. This is followed by an extensive bibliography of 57 pages and indices of mineral species, localities and subjects. The Mineralogy consists of 2 chapters, one on radioactive minerals, their composition, structure, properties, effects, and classification. The other chapter is composed of descriptions of the uranium and thorium minerals.

Part two consists of 12 chapters, which are General, Syngenetic Deposits in Igneous Rocks, Radioactive Pegmatite Deposits, Carbonatites, Pyrometasomatic and High-Intensity Hydrothermal Deposits, Mesothermal Deposits, Epithermal Deposits, Epigenetic Stratiform Deposits in Sedimentary Rocks, Phosphorites, Marine Black Shales, Placer Deposits, Radioactive Hydrocarbons, and Deposits Formed by Weathering and Ground-Water Action. From these it may be seen that the coverage is very wide. One is impressed with the completeness of the listings of occurrences and the great breadth of the author's reading. It is a monumental work.

The volume will serve as a textbook on radioactive minerals and deposits, as a supplement in courses in economic geology and unquestionably will become the leading reference book on this subject.

Coastal and Submarine Morphology. By ANDRE GUILCHER. Translated by B. W. SPARKS and R. H. W. KNEESE. Pp. 274; figs. 40; plates 8. John Wiley & Sons, Inc., 1958. Price, $6.50.

The author of this book is Professor of Oceanography at the Sorbonne and he first published it in France in 1950. This translation is based upon a revised edition.

The book has two parts, Coastal Geomorphology, and Submarine Geomorphology. In the first part are five chapters, namely, the Forces at Action, Shoreline Developments, Coastal Features Related to Sea Action, Classification of Coasts, and Coastal Evolution. He first treats of waves, currents, wind, chemical processes, and biologic factors and describes their part in shaping the coasts. The author then considers eustatic, tectonic and epeirogenic movements and their effects in shaping the coasts back of the sea. This leads into a classification of coasts such as ria and fiord coasts, glacial and unglaciated lowland coasts and those dominated by structure. Coastal evolution naturally follows. Each of these five chapters is accompanied by an extensive bibliography.

In Part II the author considers the Continental Margin and the shelf, canyons, sediments, the continental slope and the origin and evolution of submarine canyons. The last chapter deals with the deep sea floor, its relief, elevations, and deposits.

The illustrations are drawn mostly from Europe and North Africa, as are also most of the references.

The volume is informative and readable and should make a good reference book. It should also be of interest to petroleum geologists.

Clays and Clay Minerals, Annual Conference Proceedings. Edited by ADA SWINEFORD. Pp. 360. National Academy of Sciences—National Research Council, Pub. 566. Washington, D. C., 1958. Price, $4.50.

The publications of the preceding annual conferences have now become well known. This Fifth Conference was held at the University of Illinois, Oct. 8–10, 1956, under the sponsorship of the University of Illinois and the Committee on Clay Minerals of the National Research Council.

This volume consists of 29 articles contributed by 48 authors. The subject matter covers nearly all phases of general research, observations, and experimental work on the various clay minerals. It is a summation of present day research on this difficult group of minerals that adds further to our knowledge of their occurrence, their behavior under natural conditions and their origin.

Contributions in Geophysics, in Honor of Beno Gutenberg. Editors, HUGH BENIOFF, MAURICE EWING, B. F. HOWELL, JR., and FRANK PRESS. Pp. 244. International Series of Monographs on Earth Sciences, Vol. I. Pergamon Press, New York, 1958. Price, $9.00.

This volume was arranged to pay honor to Beno Gutenberg upon his retirement from the Directorship of the Seismological Laboratory of the California Institute of Technology. It is made up of 17 articles by 21 authors, all of whom are friends, colleagues, or former students. It is truly international since the contributors come from the United States, Canada, England, Sweden, Denmark, Italy, Germany, France, Netherlands, Japan, Australia and Israel.

The subjects treated cover a wide range including the various seismic phenomena, displacements, the inner core, earthquake observations, structure of the crust, geophysical history of syncline, gravity formulas, data processing, and geomagnetic drift and the rotation of the earth. The various papers picture the status of geophysical research today and will make a handy reference to all working in theoretical geophysics.

BOOKS RECEIVED

JOHN W. SALISBURY AND JAMES M. ALLEN

The Air, Conquest of Space and Time. E. B. SCHIELDROP. Pp. 256. Philosophical Library, New York, 1958. Price, $12.00. *Heavily illustrated history, principles, advancement, and future of aviation.*

Minerals Yearbook, 1956. Vol. I. Metals and Minerals (Except Fuels). STAFF OF THE BUREAU OF MINES. Pp. 1409. Price, $4.50. U. S. Govt. Printing Office, Washington, 1958. *Included are reviews of the mineral industries, of metallurgical technology, and of mining technology, with a statistical summary of mineral production and employment and injuries.*

Minerals Yearbook, 1956. Vol. III. Area Reports. STAFF OF THE BUREAU OF MINES. Pp. 1265. Price, $4.25. U. S. Govt. Printing Office, Washington, 1958. *Statistics of mineral production and use for the 48 states and the territories and possessions.*

British Borneo Geological Survey Annual Report, 1957. F. W. ROE. Pp. 200; pls. 43; figs. 31; tbls. 32. Geological Survey of British Territories in Borneo, 1958. *Summary of all work done in 1957. Exports of mineral products rose to M$376,900,000.*

British Columbia Annual Report of the Minister of Mines, 1957. W. K. KIERNAN. Pp. 176; pls. 14; figs. 4. British Columbia Department of Mines, Victoria, 1958. *Statistics of production and use of minerals, geological mapping done, mining accidents, etc.*

Rapports et Bilans de l'exercice 1957. COMITÉ SPÉCIAL DU KATANGA. Pp. 165; pls. 6; tbls. 39. Bruxelles, 1958.

The Solomon Islands—Geological Exploration and Research 1953–1956. J. C. GROVER, P. A. PUDSEY-DAWSON, and R. B. M. THOMPSON. Pp. 151; pls. 27; figs. 117. Price, £2. The Geological Survey of the British Solomon Islands Memoir No. 2, Sydney, 1958. *Contains interesting account of the Gold Ridge gold deposits of Guadalcanal.*

Expressão Econômica do Vale do Paraopeba. M. PIMENTEL DE GODOY. Pp. 149; pls. 64; figs. 20. Depart. de Águas e Energia Elétrica, Belo Horizonte, 1957. *A report on the mineral, agricultural and hydroelectric potentialities of the Paraopeba River valley in the State of Minas, Brazil. In Portuguese.*

Über Aufbau und Altersgliederung des Rheinischen Braunkohlenbeckens. ULRICH JUX and H. D. PFLUG. Pp. 48; figs. 11. Geologie, Jahrgang 7, Bieheft NR. 20, Berlin, 1958. *Entirely in German.*

The Geology of the Volta River Project. W. B. TEVENDALE. Pp. 119; pls. 24; figs. 3, tbls. 19. Ghana Geological Survey Bull. 20., Accra, 1957. *The Volta River Project is a scheme for damming the River Volta and utilizing the power produced to smelt Ghana bauxite. The report covers all aspects of the detailed geological investigations made to evaluate the bedrock conditions at alternative dam sites and within the reservoir area.*

Geology and Mineral Resources of Ada and Canyon Counties. C. N. SAVAGE. Pp. 94; figs. 27; tbls. 4. Idaho Bureau of Mines and Geology, County Rept. No. 3, Moscow, 1958. *Analysis of the nature and extent of the mineral resources of the two counties; extraction and processing techniques; the availability of power, transportation facilities, labor and technical know-how; and present as well as future markets.*

The Strawberry-Keystone Gold-Tungsten Property Pony Mining District, Madison County, Montana. R. R. REID. Pp. 19; pls. 6. Montana Bureau of Mines and Geology Information Circular 24, Butte, 1958. *The Strawberry mine lies in a northwest-trending zone of small stocks along which scheelite has been found at several places. Intensive prospecting in this zone may disclose other important deposits of scheelite.*

Forty-sixth Annual Report by the State Inspector of Mines to the Governor of the State of New Mexico for the Year Ending June 30, 1958. Pp. 66. Office of the State Inspector of Mines, Albuquerque, 1958. *Total production, exclusive of oil and gas, was $130,211,267.00, a decrease of $34,086,227.00 as compared to the preceding year.*

Geology and Mineral Resources of Morgan County. D. L. NORLING. Pp. 124; pl. 1; figs. 22. Ohio Geological Survey, Bull. 56, Columbus, 1958. *A study of the stratigraphy, structure and economic resources of an area in southeast Ohio.*

Massnahmen zur Förderung der privaten Kapitalbildung im Portugiesischen Reich. Pp. 248. Staatswissenschaftliche Studien, Zurich, 1958. *Problems of financing in underdeveloped countries; fiscal policies of the Salazar Government. In German.*

Recent Landslide Phenomena in the Rungwe Volcanic Area, Tanganyika. E. G. HALDEMANN. Pp. 14; pls. 7. Journal of the Tanganyika Society, Tanganyika Notes and Records, No. 45, Dar es Salaam, 1956. *Extremely high rainfall over short lengths of time has produced numerous landslide phenomena which are described in detail.*

List of Publications and Maps. Pp. 38. Virginia Division of Mineral Resources, Charlottesville, 1958. *List of maps of and publications of the Division, with price and availability.*

Publications of the Geological Survey, May, 1958. STAFF OF THE U. S. GEOLOGICAL SURVEY. Pp. 455. *May be obtained free on application to the Geological Survey, Washington 25, D. C. U. S. Govt. Printing Office, Washington, D. C., 1958. Contains a complete list to May, 1958, of Geological Survey annual reports, monographs, professional papers, bulletins, water-supply papers, circulars, chapters and volumes of Mineral Resources of the U. S. (1882–1923), folios of the Geologic Atlas of the U. S., and the World Atlas of Commercial Geology. Indexed according to states, areas, subjects and authors.*

Bureau of Mineral Resources, Geology and Geophysics—Melbourne, Australia, 1957–1958.

The Australian Mineral Industry—Quarterly Review and Quarterly Statistics. Vol. 11, No. 1. Pp. 19; tbls. 17. Price, 3 sh. *Statistics of mineral production and use January to April 1958.*

Bull. 36. The Geology of the Fitzroy Basin, Western Australia. D. J. GUPPY, A. W. LINDNER, J. H. RATTIGAN, and J. N. CASEY. Pp. 116; pls. 10; figs. 2; tbls. 7. *The stratigraphy, structure, sedimentary environments, petroleum prospects, and water supply of the Fitzroy Basin are described, and the more important structural and petroleum accumulation problems are discussed.*

Bull. 48. Permian Foraminifera of Australia. IRENE CRESPIN. Pp. 197; tbls. 10; map. *Description and occurrence of 106 species of Permian foraminifera.*

California Division of Mines—San Francisco, 1958.

Spec. Rept. 51. Economic Geology of the Darwin Quadrangle Inyo County, California. W. E. HALL and E. M. MACKEVETT. Pp. 73; pls. 9; figs. 34; tbls. 13. Price, $2.50. *Lead-silver-zinc, tungsten, and talc deposits occur on the margins of the Cosa batholith. Fractures have controlled the deposition of most ore bodies.*

Vol. 54, No. 2. California Journal of Mines and Geology. Pp. 296; pls. 3; figs. 46. Price, $1.00. *Two papers—effect of clay mineral composition on sediment strength, and sand and gravel resources of Cache Creek.*

Vol. 54, No. 3. California Journal of Mines and Geology. Pp. 105; pl. 1; figs. 68. Price, $1.00. *Two papers—diatomaceous earth deposit, Inyo County, and mineral resources of Tulare County.*

California Mineral Production, 1957. Pp. 12; figs. 9. Vol. 11, No. 11, Mineral Information Service. *Statistics of mineral production; sections on mining on power site lands, sandblasting.*

Bureau de Recherches Géologiques, Géophysiques et Minières—Paris, 1958.

Revue de l'Industrie Minière Française en 1957. Annales de Mines, Août-Septembre, 1958. Pp. 157. *Several papers on mineral production and use in France and its colonies. In French.*

La Chronique des Mines d'Outre-Mer et de la Recherche Minière. Pp. 246–276; figs. 2; tbls. 10. 26e Annee, No. 267, Septembre, 1958. *Contains one article on tin pegmatites, more than 25 abstracts, and various African statistics and reports.*

Illinois Geological Survey—Urbana, 1958.

Circ. 251. Hydraulic Fracture Theory. Pt. 1.—Mechanics of Materials. J. M. CLEARY. Pp. 24; figs. 12. *Some theories on the mechanics of materials are adapted for use in dealing with problems of hydraulic fracture mechanics and also to help describe conditions of stress in porous sediments.*

Circ. 252. Hydraulic Fracture Theory. Pt. II.—Fracture Orientation and Possibility of Fracture Control. J. M. CLEARY. Pp. 19; figs. 3. *Hydraulic fracture orientation and distribution are controlled by the condition of stress underground. Horizontal stress underground is altered by pore pressure.*

Circ. 253. Tiskilwa Drift-Gas Area Bureau and Putnam Counties, Illinois. W. F. MEENTS. Pp. 15; figs. 8; tbl. 1. *The gas is apparently contaminated with air near the Illinois River bluffs, but is purer farther back from the bluff line. Records of gas well pressures and barometric pressures show close correlation.*

Circ. 255. Three Ostracode Faunas from Lower and Middle Mississippian Strata in Southern Illinois. R. H. BENSON and CHARLES COLLINSON. Pp. 26; pls. 4; figs. 14; tbls. 2. *Six new species are described. The fauna indicates that at least the lower part of the Springville (State Pond Member) is of the same age as the Fern Glen (early Valmeyer).*

Circ. 257. Mineral Production in Illinois in 1957. W. L. BUSCH. Pp. 39; figs. 8; tbls. 19. *Variety, amounts, and values of minerals produced in Illinois for 1956 and 1957 are summarized.*

Circ. 258. Relation of Silurian Reefs to Ordovician Structure in the Patoka Oil Area. T. W. SMOOT. Pp. 20; figs. 11. *Results of this study indicate that production from the Kimmswick ("Trenton") limestone might be extended northeastward and southwestward from the Fairman pool.*

Circ. 259. Fuels and Power in Manufacturing Industries. W. H. VOSKUIL. Pp. 25; tbls. 33. *Compares quantities and costs of each of the fuels used in manufacturing in 1947 and 1954. Changes in the cost of each fuel and in quantity and cost per worker are reported for each type of manufacturing.*

Geological Survey of India—Delhi, 1955–1957.

Memoirs. Vol. 83. Petrology of Indian Coals. P. N. GANJU. Pp. 99; pls. 15. Price, 8 sh. *A microscopic study and classification of Indian coals.*

Bull. 12. Limestone and Dolomite Deposits in Gangpur, Sundargarh District, Orissa. S. NARAYANASWAMI, MUKTI NATH, and A. R. GOKUL. Pp. 52; pls. 8; tbls. 8. Price, 6 sh., 3 d. *Location, distribution and character of limestone and dolomite deposits.*

Bull. 14. The Manganese-Ore Deposits in Udaipur and Banswara, Rajasthan. B. C. ROY. Pp. 31; pls. 3; figs. 3; tbls. 10. Price, 2 s. 6 d. *Both replacement and bedded deposits occur within the area, and estimation of ore reserves is attempted for only three of the eleven deposits. Probable reserves for these three, 250,000 tons.*

Records. Vol. 84, Pt. 4. Pp. 80; pls. 5; figs. 8. Price, 7 sh. *A number of papers dealing with paleontology and stratigraphy.*

Geological Survey of Japan—Hisamoto-chō, Kawasaki-shi, 1958.

Bulletin. Vol. 9, No. 7. Pp. 51; figs. 40; tbls. 24. *Two papers dealing with hydrothermal uranium deposits, and one dealing with the application of geophysical methods in the search for radioactive placer deposits. In Japanese; English abstracts.*

Bulletin. Vol. 9, No. 8. Pp. 66; figs. 33; tbls. 26. *Four papers dealing with ground water, manganiferous iron deposits and mylonitic conglomerates. In Japanese; English abstracts.*

Kansas Geological Survey—Lawrence, 1958.

Bull. 130, Pt. 4. Flowage in Rock Salt at Lyons, Kansas. L. F. DELLWIG. Pp. 165–175; pls. 2; figs. 3. *Measurable and even visible flowage of salt occurs as early as 30 days after the opening of a room. The report is concerned with the cause, magnitude, and results of flowage.*

Bull. 131. Ground-Water Levels in Observation Wells in Kansas, 1957. V. C. FISHEL and B. J. MASON. Pp. 36; figs. 24; tbls. 5. *Record of measurement of water levels in 775 wells in Kansas.*

Bull. 132. Geology and Ground-Water Hydrology of the Ingalls Area, Kansas. G. J. STRAMEL, C. W. LANE, and W. G. HODSON. Pp. 152; pls. 3; figs. 34; tbls. 12. *Data of ground water occurrence, character and flow, storage and irrigation possibilities.*

Bull. 133. Oil and Gas Developments in Kansas During 1957. E. D. GOEBEL, P. L. HILPMAN, A. L. HORNBAKER, and D. L. BEENE. Pp. 264; pls. 3; figs. 3; tbls. 61. *Kansas oil production in 1957 totaled 124,054,043 barrels, a decline of 0.3% from the previous year. Proved reserves of crude oil are 947.5 million barrels, and proved reserves of natural gas are almost 17.6 trillion cubic feet.*

Northern Rhodesia Geological Survey—Lusaka, 1958.

Occasional Paper 20. The Development of the Mid-Zambezi Valley in Northern Rhodesia since Early Karroo Times. R. TAVENER-SMITH. Pp. 13; figs. 2; tbl. 1. *Discussion of Karoo sedimentation and structural evolution of the present Mid-Zambesi Valley.*

Report 3. The Geology of the Kariba Area. BRIAN HITCHON. Pp. 41; pls. 13; tbls. 8. Price, £1, 10 s. *A geological investigation of the Precambrian rocks on the Northern Rhodesia side of the Kariba Gorge of the Zambezi River. When the Kariba Dam is completed, the Kariba Gorge will be the site of one of the largest man-made lakes in the world. Geologic map, scale 1 : 50,000.*

Pennsylvania Topographic and Geologic Survey—Harrisburg, 1958.

Information Circ. 11. The Mineral Industry of Pennsylvania in 1955. R. D. THOMSON. Pp. 40; tbls. 17. *Mineral production totaled $971 million, an increase of $45 million over 1954.*

Information Circ. 12. The Mineral Industry of Pennsylvania in 1956. R. D. THOMSON and M. E. OTTE. Pp. 42; tbls. 14. *Mineral production in 1956 totaled $1 billion, an increase over 1955 of $119 million.*

Information Circ. 13. Corundum Mining in the Piedmont Province of Pennsylvania. N. C. PEARRE. Pp. 9. *Corundum was last mined in Pennsylvania in 1892, and interest is largely historical.*

Bull. G29. Guide to the Highway Geology from Harrisburg to Bald Eagle Mountain. BRADFORD WILLARD, R. C. CONLIN and D. M. HOSKINS. Pp. 38; pls. 8; figs. 2; tbls. 2. *All aspects of geology covered from physiography through geologic history, structures, stratigraphy, and paleontology. Geologic strip maps, scale 1:62,500.*

Progress Rept. 153. Preliminary Report on the Chromite Occurrence at the Wood Mine, Pennsylvania. D. M. LAPHAM. Pp. 11; pls. 2. *Preliminary study suggests that the deposit is not of economic merit, but further study is necessary to arrive at a definite conclusion.*

Topographic and Geologic Atlas of Pennsylvania. A57. New Florence Quadrangle. M. N. SHAFFNER. Pp. 16; pls. 13; figs. 16; tbls. 8. Geologic map, scale 1:62,500.

Quebec Department of Mines—1958.

Ungava Bay—Ungava Peninsula. ROBERT BERGERON. Pp. 13; figs. 13. *Only about five percent of this vast area has been adequately explored for mineral resources, and it is certain that other important finds will be made.*

The Mining Industry of the Province of Quebec in 1956. Pp. 135; pls. 5. *Production of minerals for 1956, development, employment, wages, and accidents.*

List of the Principal Operators and Owners of Mines and Quarries in the Province of Quebec. Pp. 94. *Location and ownership of mining operations in Quebec.*

The Review of Russian Geology—Columbia, South Carolina, 1958.

Petroleum Geology. Vol. 2, No. 2-B. Pp. 159–212; figs. 11; tbls. 12. *Accurate, readable translations of nine Russian articles. Six months' subscription (12 issues) is $9.00.*

Petroleum Geology. Vol. 2, No. 3-A. Pp. 213–260; figs. 12; tbl. 1. *Seven articles covering oil output of beds, calculation of reserves, field exploitation, tectonics, age of platforms, and stratigraphy of part of the Lower Carboniferous.*

South Dakota Geological Survey, Vermillion, 1957–58.

Colored geological sheets, scale 1:62,500 of following quadrangles: Henry, Gregory, Brookings, Witten, South Shore ,Watertown, Estelline, Sill Lake, White, Florence, Hayte, Keyapaha, and Wewela.

Magnetometer Map of Harding and Perkins Counties. B. C. PETSCH. *Scale, 5 miles to the inch. Anomalies indicate structure.*

Oil and Gas Tests in South Dakota, 1957. A. F. AGNEW. Scale, *16 miles to the inch. Locations of wells, names, completion dates and abbreviated logs.*

Rept. of Investigations 84. Geology and Shallow Ground Water Resources of the Brookings Area, Brookings County, South Dakota. K. Y. LEE. Pp. 36; pls. 2; figs. 6; tbls. 12. *Occurrence of water in glacial drift.*

Rept. of Investigations 85. Geology and Shallow Ground Water Resources of the Watertown-Estelline Area, South Dakota. F. V. STEECE. Pp. 25; pls. 2; figs. 5; tbls. 12. *Glacial and bedrock geology, water resources.*

Tennessee Department of Conservation—Nashville, 1958.

Rept. of Investigations 4. Ground Water in the Central Basin of Tennessee. ROY NEWCOME, JR. Pp. 81; fig. 1; tbls. 32. *A progress report covering the work done to assess the water reserves of the Central basin.*

Rept. of Investigations 5. Guidebook to Geology Along Tennessee Highways. C. W. WILSON, JR. Pp. 114; figs. 12. *Brief description of geology along highways of Tennessee.*

Union of South Africa Department of Mines—Pretoria, 1957.

Bull. 23. Waterberg Coalfield Records of Boreholes 101 to 143 Drilled for the Department of Mines. J. F. CILLIE and the FUEL RESEARCH INSTITUTE. Pp. 276; pls. 2. Price 10 s. **Geologic map, scale 1 : 150,000.**

Bull. 25. Ilmenite-Bearing Sand Along the West Coast in the Vanrhynsdorp District. C. B. COETZEE, D. K. TOERIEN and D. GROENVELD. Pp. 15; pls. 2; fig. 1; tbls. 12. Price, 3 s, 3 d. *The poor quality of the ilmenite due to its relatively high vanadium content, and the remoteness of the deposits would render exploitation under present conditions unprofitable.*

State of Washington Geological Survey—Olympia, 1958.

Publications. STAFF OF THE DIVISION OF MINES AND GEOLOGY. Pp. 8. *Contains a list of all publications printed by the various Washington geological surveys. May be ordered from the Department of Conservation and Development, 335 General Administration Bldg., Olympia, Washington.*

Reprint No. 1. Ringold Formation of Pleistocene Age in Type Locality, the White Bluffs, Washington. R. C. NEWCOMB. Pp. 328–340; fig. 1. Am. Jour. Sci., Vol. 256, New Haven, Conn. *Detailed measured sections clarify some of the previous work and assist in reaching more acceptable concepts regarding the Ringold.*

Reprint No. 2. Pleistocene Sequence in Southeastern Part of the Puget Sound Lowland, Washington. D. R. CRANDELL, D. R. MULLINEAUX and H. H. WALDRON. Pp. 384–397; fig. 1. Am. Jour. Sci., Vol. 256, New Haven, Conn. *A restudy of Pleistocene deposits results in a refinement and expansion of the sequence originally described by Willis in 1898.*

Geological Society of America—New York, 1957–58.

Bibliography and Index of Geology Exclusive of North America, Vol. 22. M. SIEGRIST, M. C. GRIER and others. Pp. 771. *Contains both alphabetic author list and a subject index to the papers cited. A note in italics is usually added to the citation to indicate the scope and, where possible, the conclusions of the paper.*

Memoir 73. Metamorphic Reactions and Metamorphic Facies. W. S. FYFE, F. J. TURNER and J. VERHOOGEN. Pp. 259; figs. 108; tbls. 7. *It is no longer satisfactory to interpret metamorphic mineral assemblages as products of reactions in closed systems determined by a single physical variable such as temperature or confining pressure. The authors present a revised and amplified theory of the mineralogical evolution of metamorphic rocks as complex reactions in multicomponent systems subject to the influence of many physical variables. Unfortunately for the economic geologist, metasomatism is hardly touched upon.*

Memoir 74. Origin of Granite in the Light of Experimental Studies in the System $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2-H_2O. O. F. TUTTLE and N. L. BOWEN. Pp. 153; pls. 6; figs. 67; tbls. 20. *Deals with experimental determinations of phase-equilibrium relations in the system albite-orthoclase-quartz-water, and with the interesting application of these results to some petrologic problems.*

Memoir 75. Bibliographies of Hydrothermal and Magmatic Mineral Deposits. J. D. RIDGE. Pp. 199; figs. 11; tbl. 1. *Several indices are provided which list the deposits alphabetically, by the minerals produced, by the age of mineralization, and by their position in a modification of the Lindgren Classification. An index of authors is also given. Included are nearly all districts for which there is sufficient material readily available in print to permit the average geologist to obtain a real understanding of any one of the deposits. Excellent work.*

Special Paper 66. Structural Conversions in Crystalline Systems and Their Importance for Geological Problems. WILHELM EITEL. Pp. 183; pls. 2; figs. 93; tbls. 7. *Includes a special discussion of the complicated structural conversion phenomona of alkali and plagioclase feldspars, making possible, by detailed structural studies, important conclusions on their genetic conditions in nature and on geological thermometry.*

Special Paper 67. Bibliography and Index of Literature on Uranium and Thorium and Radioactive Occurrences in the United States. Part 5. MARGARET COOPER. Pp. 472. *Part 5 covers Conn., Del., Ill., Ind., Me., Maryland, Mass., Mich., N. H., N. J., N. H., Ohio, Penna., R. I., Vt. and Wis.*

U. S. Geological Survey—Washington, D. C., 1958.

Prof. Paper 293. Quaternary and Engineering Geology in the Central Part of the Alaska Range. CLYDE WAHRHAFTIG and R. F. BLACK. Pp. 118; pls. 10; figs. 58; tbls. 8. *Studies of glacial features and periods of glaciation in the Nenana River valley and of landslides, icings, and frost heaving and settling affecting maintenance of track bed along 63 miles of the Alaska Railroad.*

Prof. Paper 294-I. Structural and Igneous Geology of the La Sal Mountains, Utah. C. B. HUNT. Pp. 305–364; pls. 7; figs. 15; tbls. 5. *The field evidence and the inferred physical-chemical conditions can be interpreted to mean that the La Sal magmas did not evolve from a primary basalt by crystal differentiation.*

Bull. 1043-O. Geology and Coal Resources of the Walsenburg Area, Huerfano County Colorado. R. B. JOHNSON. Pp. 26; pls. 3; tbls. 4. *General geology and occurrence of high-volatile bituminous coal in late Cretaceous and Paleocene strata. Estimated reserves 667.5 million tons.*

Bull. 1046-I. Geology of Jamuba Hill Pershing County, Nevada. A. F. TRITES, JR., and R. H. THURSTON. Pp. 20; pls. 5; fig. 1. *Only small reserves of copper, tin, and uranium are known. Production will depend on the finding of new reserves.*

Bull. 1058-A. Reconnaissance for Radioactive Deposits in Southeastern Alaska, 1952. J. R. HOUSTON, R. G. BATES, R. S. VELIKANJE and H. WEDOW, JR. Pp. 31; pls. 3; figs. 4; tbls. 5. Price, 75 cents. *Significant concentrations of radioactive minerals found in the vicinity of Salmon Bay on the northeastern shore of Prince of Wales Island.*

Bull. 1059-E. Selected Annotated Bibliography of the Uranium Geology of Igneous and Metamorphic Rocks in the United States. DIANE CURTIS. Pp. 57; pl. 1. Price, 55 cts. *One hundred and seventeen references, arranged alphabetically by author, emphasizing the geologic features of rocks and minerals for which uranium determinations have been made.*

Bull. 1060-A. Geology and Construction-Material Resources of Morris County, Kansas. M. R. MUDGE, C. W. MATTHEWS, and J. D. WELLS. Pp. 61; pls. 2; figs. 2; tbl. 1. *Limestone is used for concrete aggregate, road metal, riprap, and structural stone.*

Bull. 1062. Geology and Coal Resources of the Toledo-Castle Rock District, Cowlitz and Lewis Counties, Washington. A. E. ROBERTS. Pp. 71; pls. 16; figs. 2; tbls. 9. Price, $2.00. *General geology and description of coal resources in Tertiary strata.*

Bull. 1086-B. Geophysical Abstracts 173 April–June 1958. Pp. 118. Price, 35 cts. *Abstracts of recent geophysical papers.*

Water-Supply Paper 1303. Compilation of Records of Surface Waters of the United States through September 1950. Pt. 2-A. South Atlantic Slope Basins, James River to Savannah River. J. V. B. WELLS. Pp. 325; pl. 1; figs. 2; tbls. 900. *Summary of all surface-water data collected from 1883 to September 30, 1950.*

Water-Supply Paper 1318. Compilation of Records of Surface Waters of the United States through September 1950. Pt. 14. Pacific Slope Basins in Oregon and Lower Columbia River Basin. J. V. B. WELLS. Pp. 550; pl. 1; figs. 2; tbls. 1500. *Summary of all the surface-water records from 1878 to September 30, 1950. Contains the longest continuous record of annual maximum discharge for any stream in the United States (Columbia River near The Dalles).*

Water-Supply Paper 1399. Surface Water Supply of Hawaii 1954–55. J. V. B. WELLS. Pp. 139. *Daily flow records at 116 gaging stations; discharge measurements and investigation of ground water reserves.*

Water-Supply Paper 1424. Ground-Water Factors Affecting Drainage in the First Division, Buffalo Rapids Irrigation Project, Prairie and Dawson Counties, Montana. E. A. MOULDER, F. A. KOHOUT and E. R. JOCHENS. Pp. 197; pls. 11; figs. 51; tbls. 12. *Reclamation of land by irrigation and by drainage of waterlogged areas.*

Water-Supply Paper 1428. Saline-Water Resources of North Dakota. C. J. ROBINOVE, R. H. LANGFORD and J. W. BROOKHART. Pp. 72; pl. 1; figs. 8; tbls. 9. *Description of the principal saline-water aquifers and surface-water bodies, with available analyses.*

Water-Supply Paper 1430. Quality of Surface Waters for Irrigation, Western United States 1954. S. K. LOVE. Pp. 203. Pl. 1. *Compilation of water analyses and suitability for irrigation.*

Water-Supply Paper 1463. Records of Springs in the Snake River Valley, Jerome and Gooding Counties, Idaho, 1899–1947. R. L. NACE, I. S. MCQUEEN and A. VAN'T HUL. Pp. 61; pls. 2; figs. 2; tbls. 30.

SCIENTIFIC NOTES AND NEWS

JOSEPH L. GILLSON, chief geologist of E. I. du Pont de Nemours & Co., has been nominated president-elect of American Institute of Mining, Metallurgical and Petroleum Engineers.

ROBERT G. DOYLE was recently appointed to the position of geologist with the Maine Geological Survey.

CHARLES E. CHAPIN is now a geologist for the Lucky Mc Uranium Corp. in Riverton, Wyo. For three years prior to this he had been geologist for the J. M. Huber Corp.

J. H. MOSES, chief geologist, and WILSON D. MITCHELL, assistant chief geologist, are now at the Executive Offices of Reynolds Metals Co. in Richmond, Va.

V. C. KELLEY, professor of geology at the University of New Mexico and a director of the New Mexico Mining Assn., is returning to the University after five months as visiting professor of structural geology at Columbia University.

TAISIA MAXIMOVNA STADNICHENKO, outstanding authority on the geochemistry of coals, died November 26, 1958, in Washington, D. C.

R. V. DIETRICH is spending this year as a Fulbright Research Scholar at the Mineralogisk-Geologisk Museum in Oslo. He is engaged in the investigation of "banded gneisses."

THOROLF VOGT died in Norway in early December.

The ARIZONA BUREAU OF MINES of the University of Arizona has issued a new geologic map of Yavapai County of Arizona. The map is one of the county series of maps being prepared by the Bureau and it gives the geologic setting in detail and also shows access roads and topography.

The AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS holds its Annual Meeting at Dallas, Texas, March 16–19, 1958. The main themes will be Fundamentals of Petroleum Geology, Application of Geology, and Geophysics and Economics.

IAN CAMPBELL, Professor of Geology and Executive Officer of the Division of the Geological Sciences of the California Institute of Technology, has been appointed State Mineralogist and Chief of the California State Division of Mines, effective January 12, 1959. The California Institute is placing Dr. Campbell on a leave of absence status.

SAMUEL P. ELLISON, JR., Professor of Geology at the University of Texas, will become president of the Society of Economic Paleontologists and Mineralogists on March 19. Also serving on the 1959–1960 Council will be GORDON RITTENHOUSE, Shell Development Company, Houston, Tex.; WILLIAM J. PLUMLEY, California Research Corporation; JOHN IMBRIE, Columbia University, as Secretary-treasurer; M. L. THOMPSON and C. W. COLLINSON, State Geological Survey, Urbana, Ill., as co-editors of the *Journal of Paleontology;* and JACK L. HOUGH, University of Illinois, Urbana, as editor of the *Journal of Sedimentary Petrology.*

The NATIONAL SCIENCE FOUNDATION has announced establishment of a Science Information Service designed to make scientific literature in all languages more readily available in order to shorten the time spent by scientists and engineers in searching for needed information.

G. A. SCHNELLMANN of Mackay & Schnellmann has returned from a visit to India and Iran. R. A. MACKAY has recently made a short visit to Rhodesia and the Union of South Africa. W. G. YUILL has just spent three months on work in Iran. D. J. SIMMONS, in charge of the Mackay and Schnellmann Teheran office, is on a short visit of inspection in the Sudan.

The SECOND CARIBBEAN GEOLOGICAL CONGRESS, composed of 80 delegates from the United States, Canada, the Caribbean and Central America and Europe, met at Mayaguez, Puerto Rico, January 4–9. The conference was sponsored by the University of Puerto Rico and the Puerto Rico Economic Development Administration along with private and public agencies including the United States Geological Survey. The Congress presented recent research on all aspects of the geology of the Caribbean area and showed how it is contributing to economic development, particularly in Puerto Rico.

H. C. GUNNING has resigned as Dean of the Faculty of Applied Science and R. W. Brock Professor, and Head of the Department of Geology and Geography of the University of British Columbia. Late in January he and Mrs. Gunning will take up residence in Salisbury, Southern Rhodesia, where Dr. Gunning will act as Consulting Geologist for Anglo American Corporation of South Africa Limited. His new business address is: P.O. Box 1108, Salisbury, S. Rhodesia.

ANTON GRAY recently returned to England from a visit to South Africa.

S. H. V. BOWIE reports the finding of helium in escapes of natural gas associated with faults and fissures in the underground workings of some of the gold-uranium mines of the Witwatersrand. The gas consists chiefly of methane, nitrogen, helium (8%) and minor hydrogen, oxygen, argon, CO_2, and Co.

FRANKLIN G. PARDEE, former president of American Iron Ore Association, Cleveland, has opened an office in Crystal Falls, Mich., as consulting mining engineer and geologist.

RUDOLPH C. GEBHARDT has been named manager of the Mining division of the E. J. Longyear Co., Minneapolis.

WILLIAM C. HAYES, JR., economic geologist for the Missouri Geological Survey, has been named assistant state geologist.

E. H. LINDSEY, formerly associated with The Anaconda Co., is now with Wisser & Cox, consulting geologists in San Francisco.

MEYER RUBIN, geologist with the Geochemistry and Petrology Branch of the Geological Survey received one of five awards given by the Washington Academy of Sciences to area scientists under 40 years of age "for outstanding scientific achievements." Dr. Rubin's award was for his pioneering investigations into Pleistocene chronology and rate of studies of geologic processes, applying carbon 14 methods. Since September 1955 he has been in charge of the Survey's radiocarbon dating laboratory.

The American Geological Institute has announced the appearance of a new technical journal, *International Geology Review*, containing English translations of Soviet geological material not previously available to American scientists except in the Russian language. It is being published by the Institute as a part of a comprehensive translation program conducted with the aid of grants from the National Science Foundation. Dr. Rhodes W. Fairbridge, professor of Geology at Columbia University, is chairman of the Translation Committee and director of the AGI Translation Center, 601 West 115th Street, New York City. The Institute will also publish a journal of scientific abstracts. In addition, two Russian geology books—*Tectonics* by Vladimir Belousov, a study of the structure of the earth, and

Facies Studies by Dimitri Nalivkin, a description of the nature of old sediments—have been translated under the supervision of AGI Translation Center and will appear later in 1959.

M. S. KRISHNAN, formerly Director of the Geological Survey of India, later connected with the Department of Research and Development at New Delhi, and then Director of the Indian School of Mines, has resigned from Government service to accept an assignment as Professor in the Department of Geology and Geophysics at Andhra University at Waltair, where Professor Mahadevan is in charge.

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CONTENTS

Part I

FOREWORD ii
ECONOMIC GEOLOGY ..... *Alan M. Bateman* 1
METALLOGENETIC PROVINCES AND EPOCHS ..... *F. S. Turneaure* 38
THERMAL SPRINGS AND EPITHERMAL ORE DEPOSITS ..... *Donald E. White* 99
THE CLASSIFICATION OF ORE DEPOSITS ..... *James A. Noble* 155
STRUCTURE OF HYDROTHERMAL ORE DEPOSITS ..... *H. E. McKinstry* 170
THE ZONAL THEORY OF ORE DEPOSITS ..... *Charles F. Park, Jr.* 226
TEMPERATURES IN AND NEAR INTRUSIONS ..... *T. S. Lovering* 249
SYNTHETIC MINERALS ..... *W. A. Weyl* 282
HYDROTHERMAL ALTERATION AS A GUIDE TO ORE ..... *George M. Schwartz* 300
OXIDATION OF COPPER SULFIDES AND SECONDARY SULFIDE ENRICHMENT *Charles A. Anderson* 324
METHODS AND PROBLEMS OF GEOLOGIC THERMOMETRY ..... *Earl Ingerson* 341
SEDIMENTARY DEPOSITS OF RARE METALS ..... *Konrad B. Krauskopf* 411
ORIGIN OF URANIUM DEPOSITS ..... *V. E. McKelvey, D. L. Everhart and R. M. Garrels* 464

Part II

ENGINEERING GEOLOGY—A FIFTY YEAR REVIEW ..... *Robert F. Legget* 534
INFLUENCE OF GEOLOGICAL FACTORS ON THE ENGINEERING PROPERTIES OF SEDIMENTS ..... *Karl Terzaghi* 557
RECENT DEVELOPMENTS IN CLAY MINERALOGY AND TECHNOLOGY *Ralph E. Grim* 619
PROPERTIES OF CALCIUM AND MAGNESIUM CARBONATES AND THEIR BEARING ON SOME USES OF CARBONATE ROCKS ..... *D. L. Graf and J. E. Lamar* 639
THE QUANTITATIVE APPROACH TO GROUND-WATER INVESTIGATIONS *John G. Ferris and A. Nelson Sayre* 714
TIME OF PETROLEUM ACCUMULATION ..... *A. I. Levorsen* 748
COAL PETROLOGY ..... *C. E. Marshall* 757
THE USE OF GAMMA RAY MEASUREMENTS IN PROSPECTING *William L. Russell* 835
ECONOMIC APPLICATIONS OF PALEOCOLOGY ..... *Samuel P. Ellison* 867
GEOPHYSICS APPLIED TO PROSPECTING FOR ORES ..... *Louis B. Slichter* 885
MINOR ELEMENTS IN SOME SULFIDE MINERALS ..... *Michael Fleischer* 970
THE STUDY OF PEGMATITE DEPOSITS ..... *Richard H. Jahns* 1025–1130

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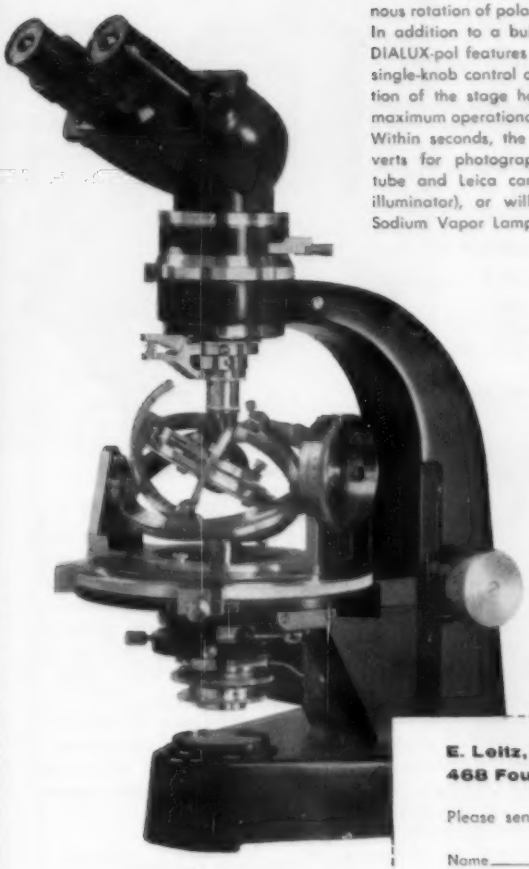

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(*Continued on Page xii*)

(*Continued from Page xi*)

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(*Continued on Page xiii*)

(*Continued from Page xii*)

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(*Continued on Page xiv*)

(*Continued from Page xiii*)

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(*Continued on Page xv*)

(*Continued from Page xiv*)

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(*Continued on Page xvi*)

(*Continued from Page xv*)

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(*Continued on Page xvii*)

(*Continued from Page xvi*)

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(*Continued on Page xviii*)

(*Continued from Page xvii*)

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(*Continued on Page xix*)

(*Continued from Page xviii*)

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(*Continued on Page xx*)

(*Continued from Page xix*)

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(*Continued on Page xxi*)

(*Continued from Page xx*)

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(*Continued on Page xxii*)

(*Continued from Page xxi*)

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(*Continued on Page xxiii*)

(Continued from Page xxii)

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